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Characterisation and Classification of RISØ P2546 Cup Anemometer

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Abstract The characteristics of the RISØ P2546 cup anemometer were investigated in detail, and all data presented in figures and tables. The characteristics include: wind tunnel calibrations, including an accredited calibration; tilt response measurements for tilt angles from -40° to 40°; gust response measurements at 8m/s, 10,5m/s and 13m/s and turbulence intensities of 10%, 16% and 23%; step response measurements at step wind speeds 4, 8, 12 and 15m/s; measurement of torque characteristics at 8m/s; rotor inertia measurements and measurements of friction of bearings at temperatures -20°C to 40°C. The characteristics are fitted to a time domain cup anemometer model, and the cup anemometer is put into the CLASSCUP classification scheme. The characteristics are also compared to the requirements to cup anemometers in the Danish wind turbine certification system and the CD of IEC 61400-121 from June 2002.

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Contents

Preface

The following report is the result of investigations and measurements made on the RISØ P2546 cup anemometer. The methods and procedures used have been developed in the European CLASSCUP project in an international cooperation. The same partners have been involved in the measurements on the RISØ P2546 cup anemometer. Jan-Åke Dahlberg of FOI in Stockholm have made all wind tunnel measurements at FOI assisted by Troels Friis Pedersen. Dieter Westermann of DEWI has made the accredited calibration at Oldenburg university. Troels Friis Pedersen of RISØ made all inertia and friction measurements, and all analysis and reporting. Ole Frost Hansen of RISØ provided details of the cup anemometer.

1 Introduction

The present report is an investigation of the characteristics of the RISØ P2546 cup anemometer. All investigations are made under laboratory conditions and the characteristics are presented in figures and tables. The characteristics are fitted to a time domain cup anemometer model, and deviations in wind speed reading are calculated for various ranges of environmental climatic conditions. The cup anemometer is put into the CLASSCUP classification scheme, Ref. 1. Characteristics are also compared to the requirements in the Danish wind turbine certification system, Ref. 2, and to the requirements in the CD (committee draft) for the IEC 61400-121 standard on power performance, Ref. 3.

2 Cup Anemometer Type Description

The cup anemometer is produced by Ole Frost Hansen, RISØ. The RISØ P2546 cup-anemometer specifications are described in Appendix A. The cup anemometer has three plastic cups, welded by ultrasound on a plastic rotor hub with a centre steel part. The cup rotor is mounted on a steel shaft, which is supported with two bearings, one at the top of the slender neck, and the other in the central part of the anemometer body. The anemometer body is made of anodised aluminium. On the bottom of the shaft, a permanent magnet is mounted horizontally. The rotational speed is measured with a reed relay, sensing on the permanent magnet. The output is a pulse signal with two pulses per rotation. Normally, the rotational speed is measured by the time of one whole revolution, updated for each half revolution. A sketch of the cup anemometer is shown in Figure 2-1.

2.1 Specific Cup Anemometer for Tests

Before the tests began, a cup anemometer was selected from a batch of twenty newly produced cup anemometers. The criteria for selecting the cup anemometer were based on friction measurements. All manufactured cup anemometers are friction tested according to the procedure in Ref. 4. The selected cup anemometer has a friction, which is average for not just the batch of cup anemometer, but for the type as such. In all other aspects the selected cup anemometer represent the average of the RISØ P2546a type, where “a” is a code for reed relay type detection of rotational speed.

The selected cup anemometer has the production serial number 840. The registration number in the RISØ VEA instrument database is PFV reg. no. 1364.

All tests are based on this selected cup anemometer.

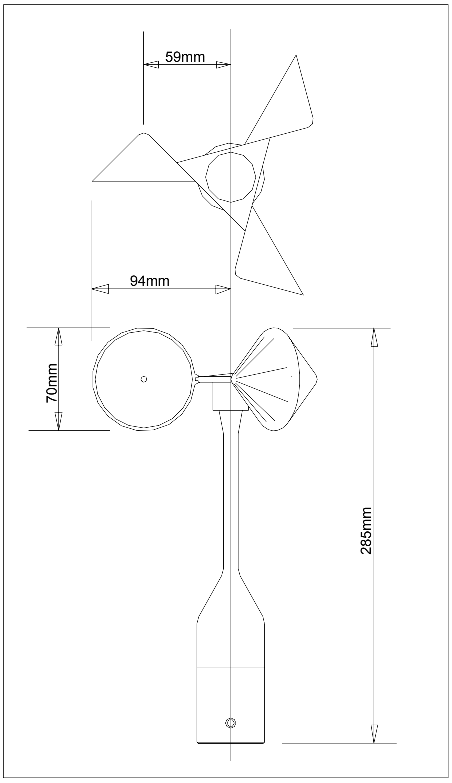

Figure 2-3 Sketch of RISØ P2546 with main dimensions

Figure 2-2 Photo of RISØ P2546 serial # 840, PFV reg. no. 1364

3 Wind Tunnel and Laboratory Tests

The characteristics of the cup anemometer have been investigated in wind tunnels and various laboratory tests. The following chapters describe each test in detail.

3.1 Wind Tunnel Calibrations

The cup-anemometer was accredited calibrated in the anechoic Oldenburg University wind tunnel by DEWI. The calibration was made according to the MEASNET calibration procedure, version 1 of September 1998, Ref. 5, and the ISO standard on measurements of fluid flow in closed conduits, Ref. 6. The accredited DEWI calibration certificate is attached in Appendix B. This calibration is the background for the analysis of the cup anemometer.

The cup anemometer was also calibrated in the non-accredited FOI LT5 wind tunnel.

The results of the two calibrations are shown in Figure 3-1 and Table 3-1, according to the calibration expression:

$$U = A_{cal} \cdot f + B_{cal}$$

where f is the pulse frequency (two pulses per revolution).

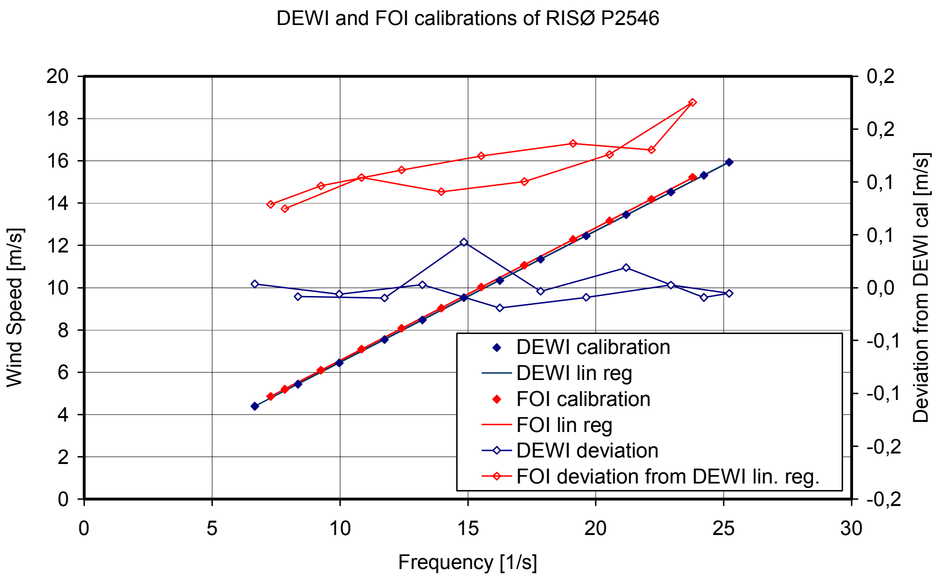

Figure 3-1 Calibrations of RISØ P2546 cup anemometer

Table 3-1 Accredited calibration by DEWI in the Oldenburg University wind tunnel and non-accredited calibration by FOI in the LT5 wind tunnel

Institute	Slope A_{cal}	Intercept B_{cal}	R^2	Wsp at 13 s^{-1}
DEWI	0.62251	0.241	0.999991	8.334
FOI	0.62684	0.289	0.999992	8.438

The calibration in the FOI LT5 wind tunnel is seen to be 1.3% higher than the calibration in the Oldenburg wind tunnel at 13Hz. This is an unacceptable high difference for comparison between accredited wind tunnels. It should be mentioned, though, that the LT5 wind tunnel in this analysis is used for tilt and dynamic tests, where relative differences are important, and not as a calibration wind tunnel. The reason for the deviation between the two wind tunnels has not been investigated.

3.2 Measurements of Angular Response

Measurements of angular response were made in the FOI LT5 wind tunnel. The tests were preceded by calibration of the tilt angle device. The cup anemometer was mounted on a Ø25 tube, that during the measurements was swept back and forth with a sweep rate of about 0,4°/sec to ±40°. Measurements were carried out for about 10 minutes in the wind tunnel. The set-up is shown in Figure 3-2.

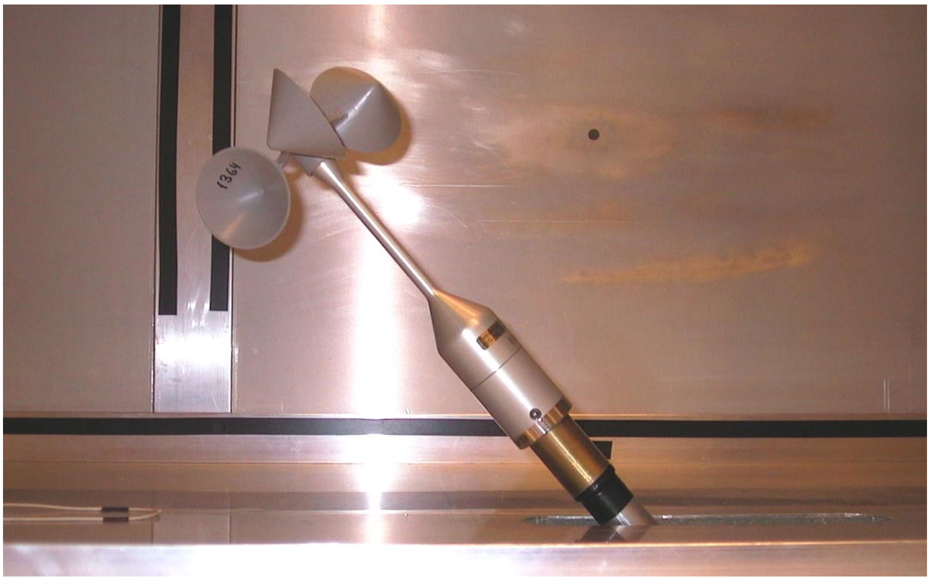

Figure 3-2 Tilt test of the RISØ P2546 cup anemometer in FOI LT5 wind tunnel; tilting angle -40° and wind coming from the right

Data were sampled at a frequency of 17Hz for each constant wind speed. All data were analysed with a method of bins analysis with a bin size of 2°. Figure 3-3 shows the result of the tilt tests at 5, 8 and 11m/s. At 8m/s the test was repeated in order to verify the reproducibility.

The measurements show an increased response of 1.5% at a tilt angle of 5°, and otherwise steep slopes below the cosine function down to about 90%, where the response flattens out and increases again at tilt angles lower than -30°. The angular response measurements are tabled in the following table.

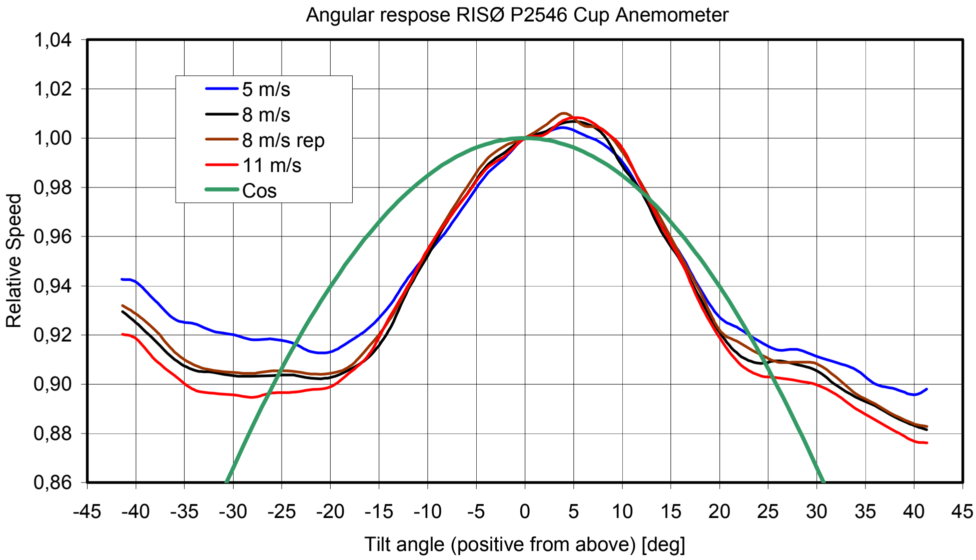

Figure 3-3 Angular response of RISØ P2546 cup anemometer

Table 3-2 Angular response of the RISØ P2546 cup anemometer

deg	5m/s	8m/s	11m/s
-41,4	0,9426	0,9295	0,9203
-40,0	0,9416	0,9250	0,9185
-38,0	0,9340	0,9176	0,9099
-36,0	0,9263	0,9100	0,9034
-34,0	0,9246	0,9057	0,8977
-32,0	0,9215	0,9048	0,8963
-30,0	0,9201	0,9034	0,8957
-28,0	0,9181	0,9033	0,8947
-26,0	0,9183	0,9034	0,8965
-24,0	0,9169	0,9038	0,8967
-22,0	0,9133	0,9025	0,8978
-20,0	0,9131	0,9027	0,8989
-18,0	0,9174	0,9060	0,9047
-16,0	0,9230	0,9112	0,9122
-14,0	0,9315	0,9218	0,9266
-12,0	0,9433	0,9386	0,9401
-10,0	0,9530	0,9521	0,9545
-8,0	0,9626	0,9661	0,9663
-6,0	0,9740	0,9771	0,9770
-4,0	0,9849	0,9883	0,9873
-2,0	0,9922	0,9944	0,9930
0,0	1,0000	1,0000	1,0000
2,0	1,0022	1,0025	1,0014
4,0	1,0043	1,0062	1,0073
6,0	1,0014	1,0062	1,0080
8,0	0,9976	1,0015	1,0032
10,0	0,9904	0,9887	0,9960
12,0	0,9779	0,9778	0,9802
14,0	0,9645	0,9622	0,9645
16,0	0,9528	0,9500	0,9502
18,0	0,9387	0,9348	0,9328
20,0	0,9272	0,9210	0,9189
22,0	0,9227	0,9120	0,9086
24,0	0,9176	0,9085	0,9037
26,0	0,9139	0,9095	0,9026
28,0	0,9141	0,9080	0,9014
30,0	0,9113	0,9055	0,8998
32,0	0,9088	0,8996	0,8958
34,0	0,9060	0,8948	0,8901
36,0	0,9001	0,8912	0,8855
38,0	0,8981	0,8867	0,8810
40,0	0,8957	0,8832	0,8769
41,3	0,8980	0,8816	0,8761

3.3 Dynamic Overspeeding Measurements

Dynamic overspeeding was measured in the FOI LT5 wind tunnel, following the procedure of Ref. 1. Gusts were generated with two rotating vanes in the outlet section. By rotating the vanes, the wind speed in the wind tunnel is varied almost sinusoidal up to frequencies of 2Hz. The tests with the RISØ P2546 cup anemometer were preceded by calibration of an angle response test of the propeller anemometer that was used as reference for the gust tests and by quite extensive tests to verify the placement of the reference propeller anemometer.

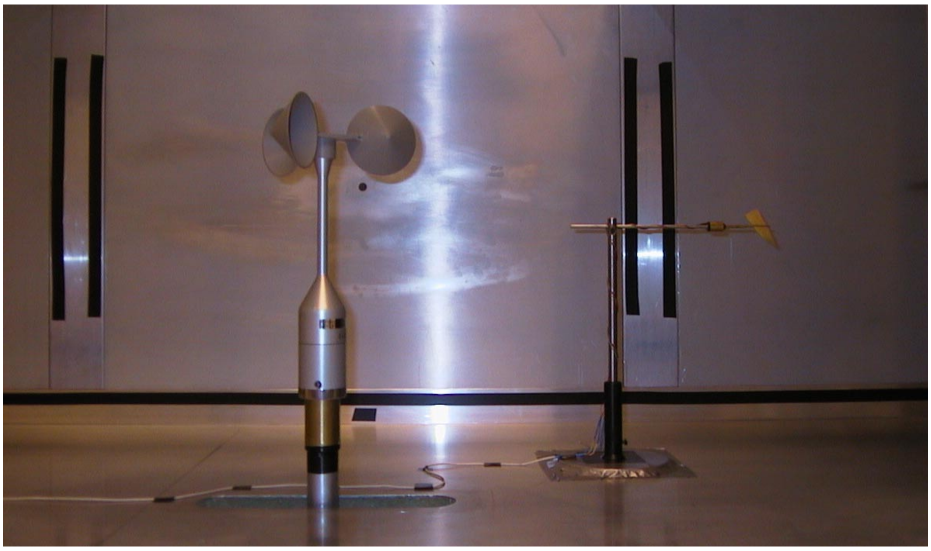

Figure 3-4 Investigations on propeller positioning in the wind tunnel, with actual position used in the tests (wind is coming from the right)

Tests with the propeller anemometer placed at three different upwind locations (right, centre and left) in front of the cup anemometer showed no significant difference. The position with the propeller to the right of the anemometer, as seen in the wind direction, was selected for all gust tests.

The dynamic overspeeding test procedure used is a relative test procedure, where the relative overspeeding of the cup anemometer is related to the fast responding propeller anemometer. The response characteristics of the propeller anemometer was not analysed in detail, but it was anticipated to be substantially faster than the cup anemometer at the applied frequencies. The tests were conducted over a period of 30 seconds, and the number of pulses of the cup anemometer was related to the number of pulses of the propeller anemometer.

The reference pulse-frequency ratio was measured at the lowest gust frequency of 0,033 Hz in the wind tunnel instead of at constant wind speed. This was made because the wind tunnel could be kept in a constant gust mode during all measurements. The reference conditions at 0,033 Hz were instead frequently repeated throughout the test.

Three tests were carried out at 8m/s. Three measurements were made at each gust frequency. In the figures, the average of the three measurements is also shown. The overspeeding at the highest frequencies are for the turbulence intensities 10%, 16% and 23%, in the order of -0,1%, 0,5% and 1,8%.

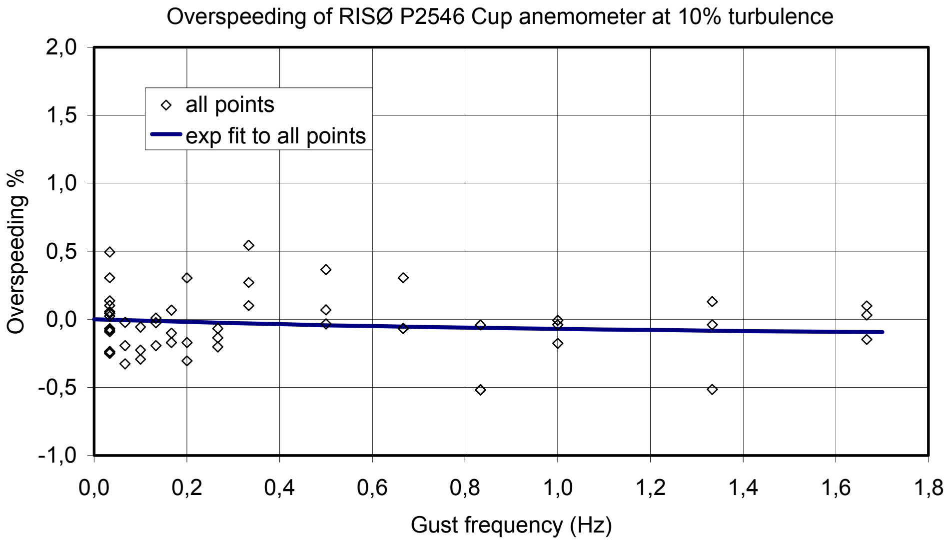

Figure 3-5Overspeeding of RISØ P2546 cup anemometer at 8m/s and 10% turbulence

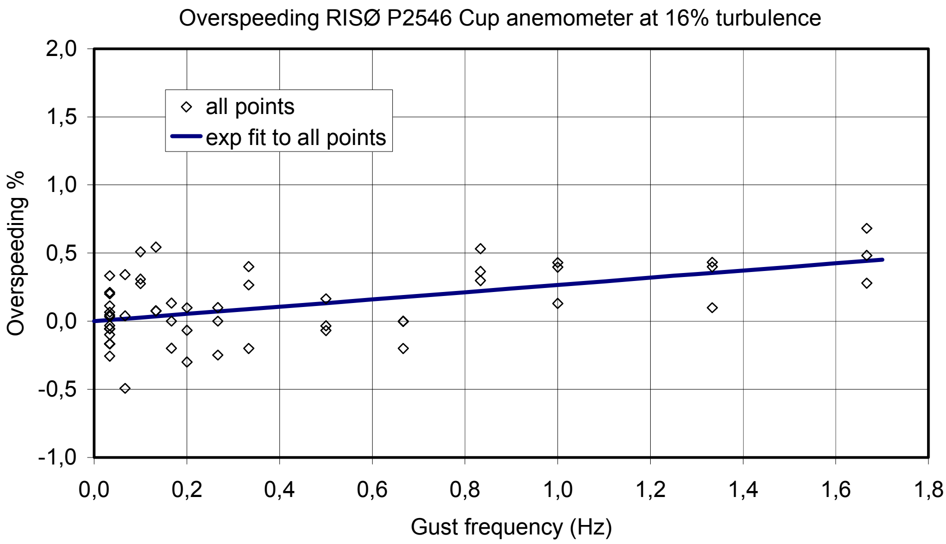

Figure 3-6 Overspeeding of RISØ P2546 cup anemometer at 8m/s and 16% turbulence

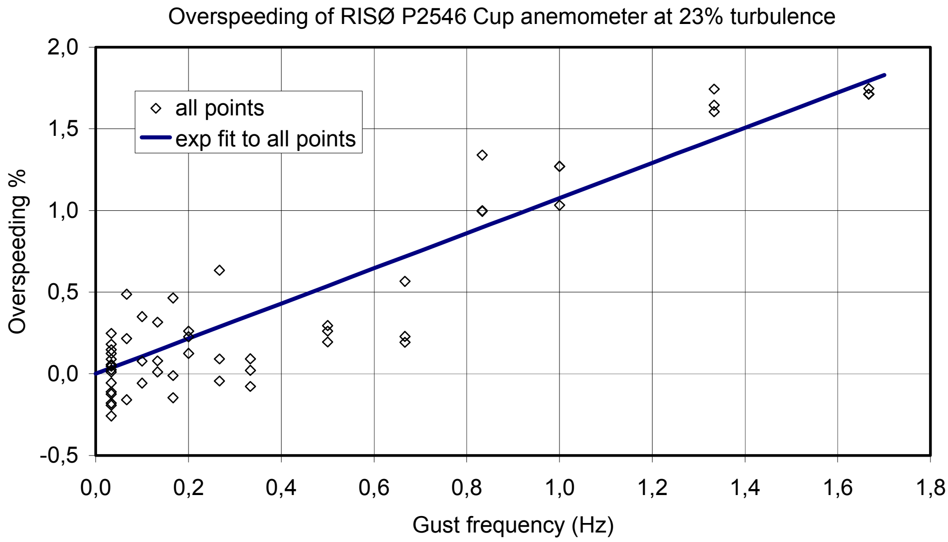

Figure 3-7 Overspeeding of RISØ P2546 cup anemometer at 8m/s and 23% turbulence

The overspeeding at all turbulences is seen to spread with almost 1%. At both 10% and 16% turbulence the overspeeding at all frequencies is very small, and does not seem to be above 0,5°. At 23% turbulence the overspeeding increases after 0,7Hz and reaches a level between 1,5 and 2%.

3.4 Measurements of Torque Characteristics

The measurement of the torque characteristics was made at FOI in Sweden with the use of a special balance, according to Ref. 1. A thin rod was attached to the top of the cup anemometer (seen in the photo below). The rod was passed through the top of the tunnel roof (small hole in white paper) and attached to a motor (dark rotational symmetric body). The motor was attached to a shaft that was mounted in two bearings so that the motor could rotate. The shaft was held in place by a balance, mounted on a clamp on the shaft. The balance was calibrated after the measurements.

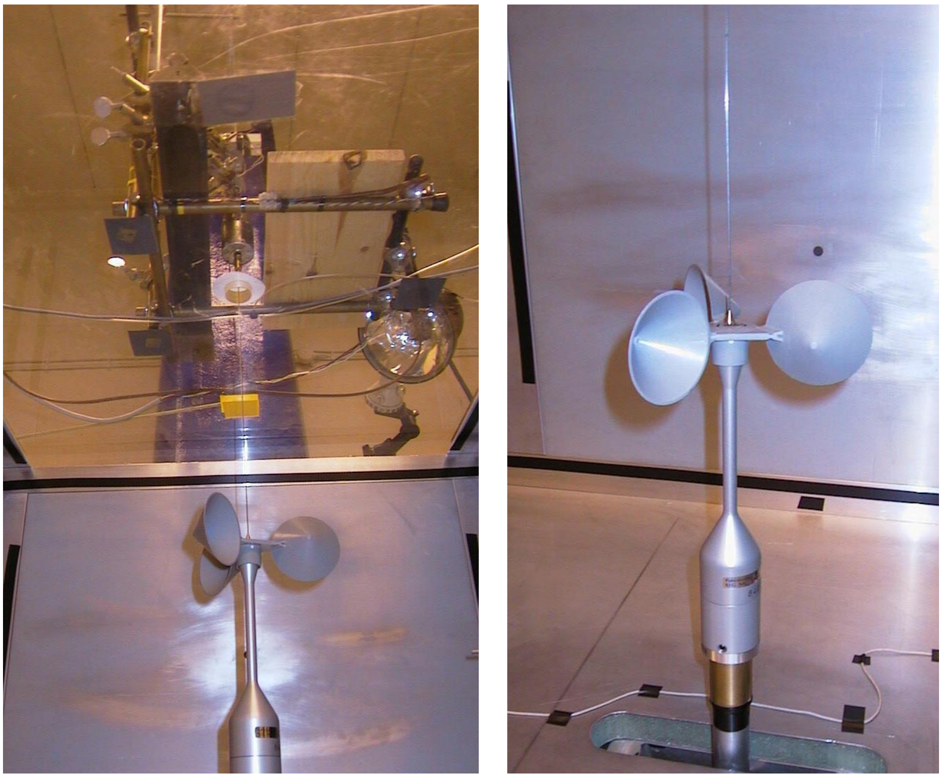

Figure 3-8 Test set-up for rotor torque measurements with thin rod mounted on top of cup anemometer and going through hole in ceiling to motor and strain gauge bridge measurement system mounted above transparent wind tunnel ceiling

Figure 3-9 Torque measurement system with motor in torpedo like housing, bearings on spring loaded mounting rod in grey housing and spring balanced strain gauge bridge attached to the mounting rod to the left of the light grey attachment fixture

Torque measurements were carried out at 8 m/s at various rotational speeds, concentrated around equilibrium tip speed ratio. For each point a 30sec measurement was made. The results are shown in the following table and figure.

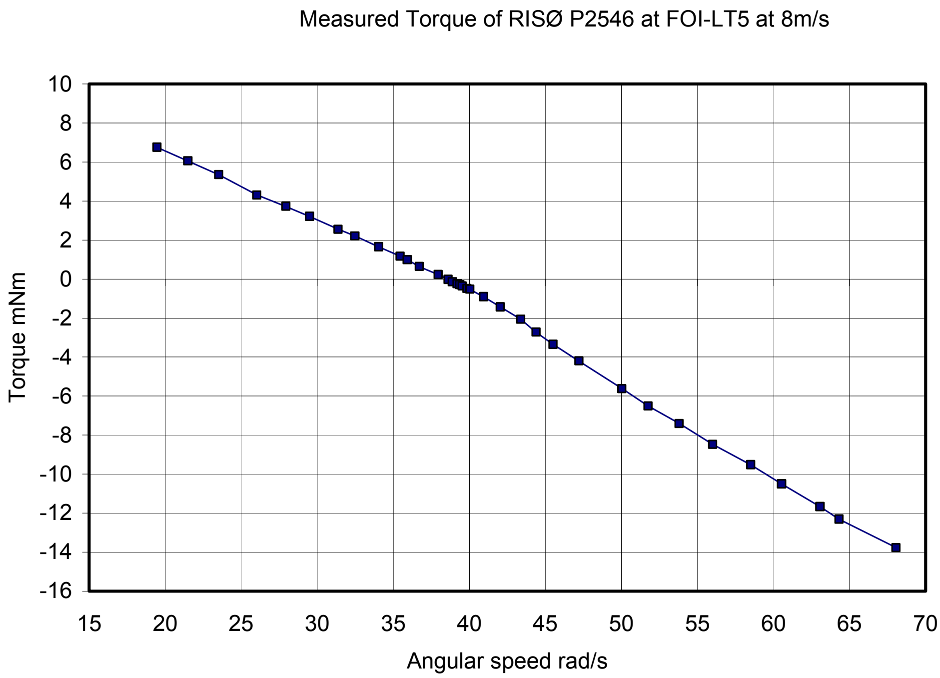

Figure 3-10 Torque measurements at FOI at 8m/s on the RISØ P2546 cup anemometer

Table 3-3Table of measured torque of RISØ P2546 cup anemometer

Wind speed	Angular speed	Torque
m/s	rad/s	mNm
7,97	19,46	6,759
7,98	21,49	6,056
7,98	23,53	5,347
7,99	26,04	4,300
8,00	27,94	3,722
7,97	29,49	3,205
7,98	31,37	2,545
8,00	32,47	2,205
7,99	34,04	1,652
7,97	35,45	1,173
7,98	35,92	0,987
8,00	36,70	0,632
7,99	37,96	0,220
8,00	38,61	-0,022
8,00	38,90	-0,146
7,99	39,21	-0,236
8,01	39,37	-0,296
8,01	39,52	-0,358
7,99	39,84	-0,498
8,00	40,03	-0,526
8,01	40,94	-0,914
8,01	42,04	-1,433
8,01	43,38	-2,060
8,01	44,39	-2,725
8,02	45,51	-3,354
8,01	47,21	-4,201
8,02	50,04	-5,625
8,02	51,76	-6,504
8,01	53,80	-7,412
8,03	56,00	-8,476
8,03	58,50	-9,522
8,02	60,54	-10,509
8,04	63,06	-11,669
8,03	64,31	-12,315
8,04	68,07	-13,782

3.5 Step Response Measurements

Step response measurements are not generic for determination of the characteristics of the cup anemometer. They were made to check the time domain model. The measurements were carried out according to the IEA recommended procedure in Ref. 4, at four different wind speeds The anemometer was released from stand still and accelerated until balance with the constant wind speed. The time trace of the pulse train was recorded and an exponential curve was fitted to the data:

$$U = U_0(1 - \exp(-\frac{t}{\tau}))$$

where $\tau = l_0 / U_0$ and U_0 is the step in wind speed from 0m/s.

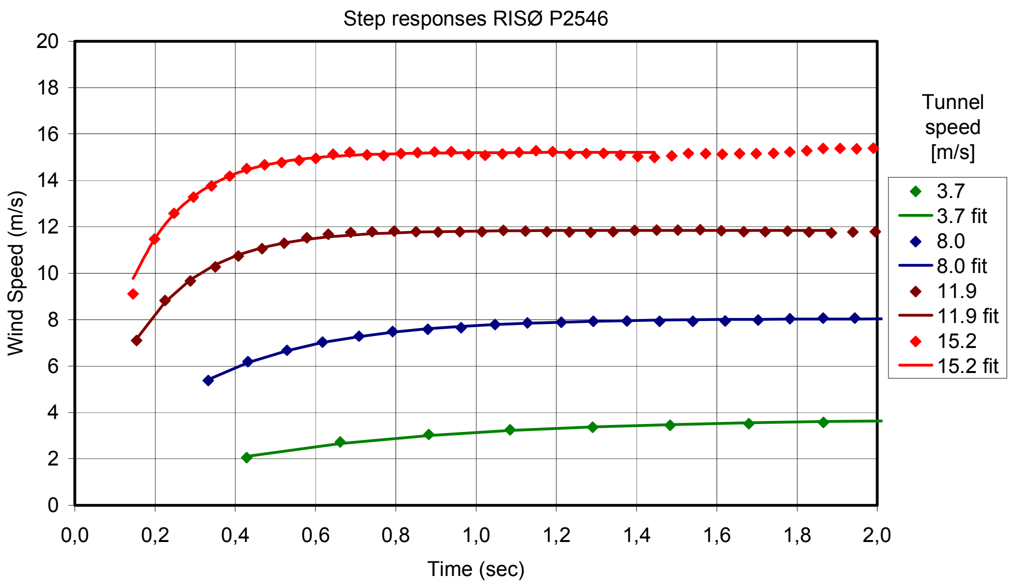

Figure 3-11 Step responses of RISØ P2546 cup anemometer at 3.7, 8.0, 11.9 and 15.2m/s

The following results were achieved.

Table 3-4 Fitted step response measurements of RISØ P2546 cup anemometer

Wind speed m/s	Distance constant in m			Average
	Test 1	Test 2	Test 3	
3,7	2,17	2,13	2,12	2,14
8,0	2,36	2,14	2,47	2,32
11,9	2,34	2,10	2,02	2,15
15,2	2,00	2,18	2,35	2,18
Overall average				2,20

The overall average of the distant constant measurements is 2,20m. The measurement procedure, though, has a high uncertainty due to a little resolution of only to pulses per revolution. Any dependency of the wind speed level cannot be concluded from the measurements.

3.6 Measurement of Rotor Inertia

The rotor inertia was measured on the rotor itself, dismantled from the cup anemometer body. The rotor was weighed and mounted in three wires to oscillate freely around its shaft, Figure 3-12.

Figure 3-12 Measurement of inertia of cup anemometer

From the oscillations, the inertia can be found from the formula:

$$I = \frac{T^2 M g r^2}{4\pi^2 l}$$

where:

T	is average time of one oscillation
M	is mass of rotor
r	is radius from axis of rotation to the three strings
l	is the length of the strings
g	is gravity acceleration 9,81m/s^2

For the RISØ P2546 cup anemometer, the values are:

$M = 0,062kg$

$r = 0,075m$

$l = 0,875m$

Three measurements were made. The results are shown in Table 3-5.

Table 3-5 Measurements of inertia of the rotor on the RISØ P2546 cup anemometer

No.	T sec
1	1,010
2	1,005
3	1,007

Average oscillation time is $T = 1,007\,\sec$. The rotor inertia is:

$I = 1,01 \cdot 10^{-4}\,kgm^2$

The shaft inertia in insignificant. When added, it does not increase the number on the second decimal.

3.7 Measurement of Friction Characteristics

The friction in the bearings of the cup anemometer was measured with a flywheel test. The rotor was dismantled from the cup anemometer. A flywheel with the same weight as the rotor was mounted on the cup anemometer shaft.

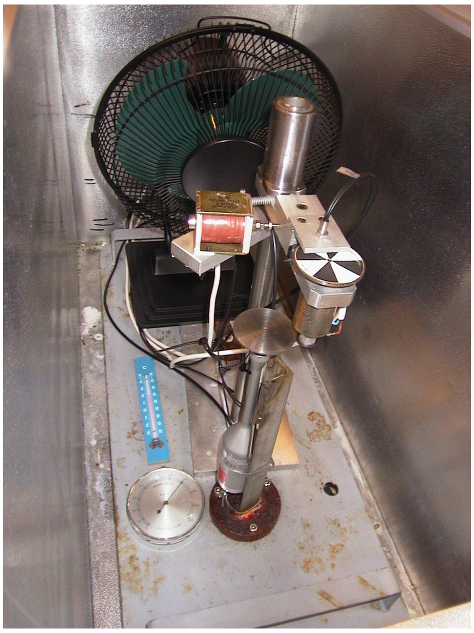

Figure 3-13 Setup in climate chamber

Figure 3-14 RISØ P2546 cup anemometer body with flywheel

The flywheel characteristics were: weight 51g, radius 0,030m, inertia 2,30*10^{-5} kgm^2. The tests were carried out in a closed and temperature stabilised climate chamber. Temperature was controlled with a control system, and the air inside the climate chamber was circulated with an air ventilator. The temperature could be controlled within ±0,3°C. A stable temperature was established for each 5°C or 2°C. The anemometer was at each temperature rotated for a while to establish stationary temperature conditions in the bearings.

In order to keep stable temperature environments, all tests were made with external excitation of the flywheel. An electric motor was set to start rotation of the flywheel on the cup anemometer at a rotational speed corresponding to

24m/s. After release, the rotational speed was measured during deceleration of the rotor.

The describing differential equation of the deceleration is:

$$I\frac{d\omega}{dt} = -F(\omega) - 0.616\pi\rho R^4 (\nu\omega^3)^{1/2}$$

where $F(\omega)$ is the friction in bearings as function of angular speed, and the second term is the air friction of the flywheel with the radius R. The friction in bearings is determined by rearranging:

$$F(\omega) = -I\frac{d\omega}{dt} - 0.616\pi\rho R^4 (\nu\omega^3)^{1/2}$$

A third degree polynomial was fitted to the deceleration, and the derivative was taken from the fit. The friction was again fitted to a second order polynomial.

$$F(\omega) = f_1 + f_2\omega + f_3\omega^2$$

The following figures show measured decelerations and fitted friction of five tests at -18°C. The results are seen to be reasonably stable.

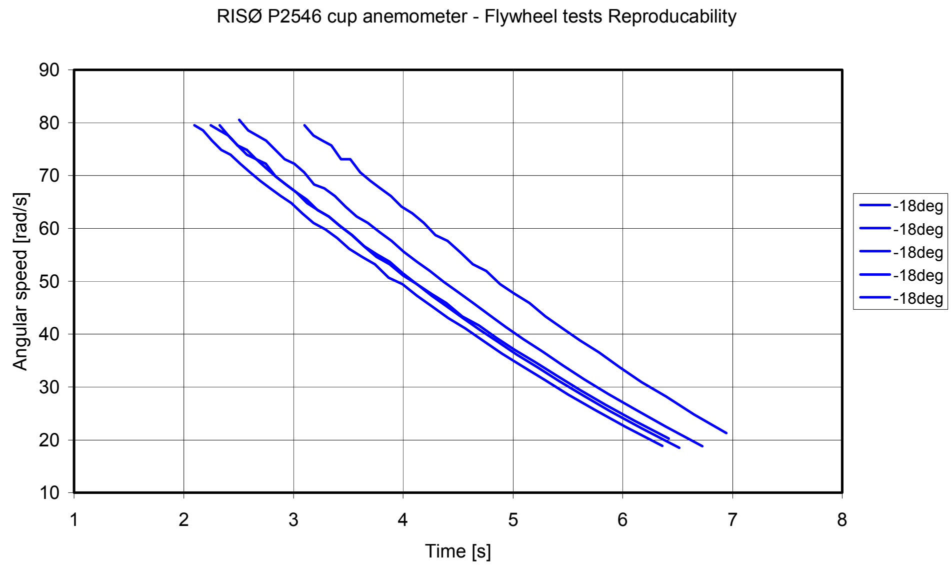

Figure 3-15 Five deceleration tests of RISØ P2546 cup anemometer with fly-wheel

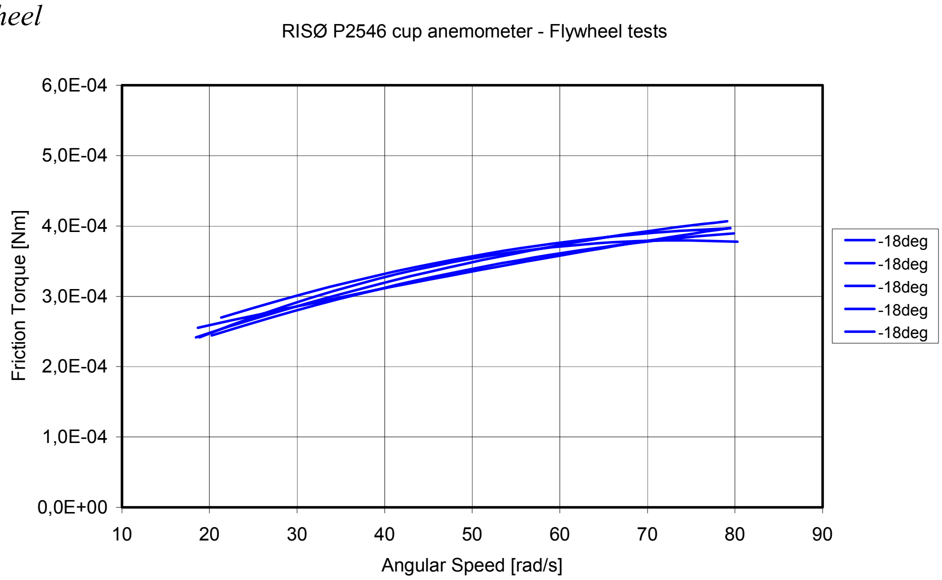

Figure 3-16 Five friction torque measurements of RISØ P2546 cup anemometer

Figures 3-17 and 3-18 show measured friction at temperatures form 40°C to -20°C at two different Y-axis scales.

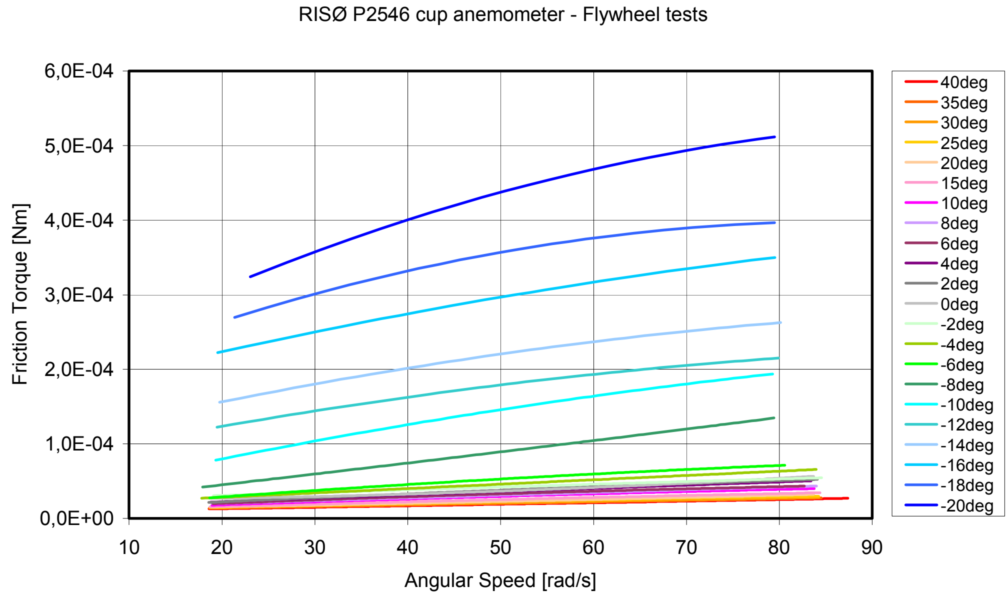

Figure 3-17 Decelerations of RISØ P2546 rotor with flywheel at temperatures40 ℃ to -20 ℃

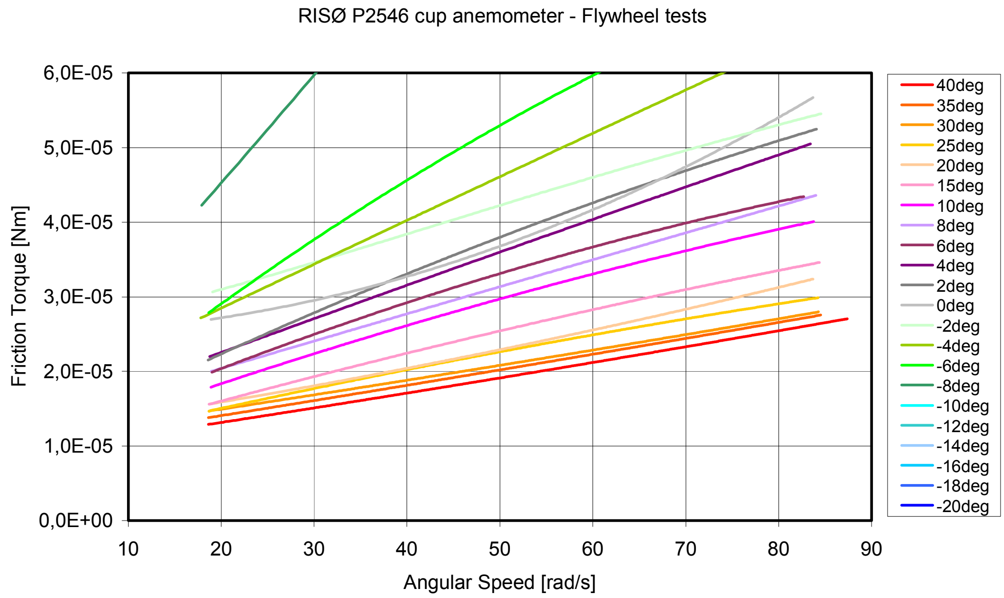

Figure 3-18 Friction torque of RISØ P2546 cup anemometer at temperatures 40 ℃ to -20 ℃; increased scale to show friction at high temperatures

All friction coefficients are summarized in the following table.

Table 3-6 Friction coefficients of RISØ P2546 cup anemometer and friction at 8m/s

Temperature	f_1 Nm	f_2 Nm/s	f_3 Nm/s^2	friction at 40 rad/s Nm
40°C	9,37e-6	1,85e-7	1,97e-10	1,71e-5
35°C	1,01e-5	1,95e-7	1,29e-10	1,81e-5
30°C	1,12e-5	1,82e-7	1,99e-10	1,88e-5
25°C	9,37e-6	2,97e-7	-6,35e-10	2,02e-5
20°C	1,19e-5	1,83e-7	7,32e-10	2,04e-5
15°C	9,03e-6	3,64e-7	-7,26e-10	2,24e-5
10°C	9,67e-6	4,57e-7	-1,12e-9	2,62e-5
8°C	1,30e-5	3,70e-7	-7,41e-11	2,77e-5
6°C	1,02e-5	5,46e-7	-1,73e-9	2,92e-5
4°C	1,34e-5	4,64e-7	-2,31e-10	3,16e-5
2°C	1,04e-5	6,26e-7	-1,50e-9	3,31e-5
0°C	2,51e-5	2,04e-8	4,27e-9	3,27e-5
-2°C	1,46e-5	6,46e-7	-1,65e-9	3,78e-5
-4°C	1,66e-5	5,96e-7	-1,21e-10	4,02e-5
-6°C	9,91e-6	1,02e-6	-3,19e-9	4,56e-5
-8°C	1,71e-5	1,38e-6	1,22e-9	7,44e-5
-10°C	2,63e-5	2,87e-6	-9,60e-9	1,26e-4
-12°C	7,57e-5	2,61e-6	-1,09e-8	1,63e-4
-14°C	1,01e-4	3,00e-6	-1,23e-8	2,02e-4
-16°C	1,64e-4	3,18e-6	-1,06e-8	2,75e-4
-18°C	1,74e-4	5,13e-6	-2,92e-8	3,32e-4
-20°C	1,93e-4	6,37e-6	-2,97e-8	4,00e-4

The friction as function of temperature is plotted in the following figure.

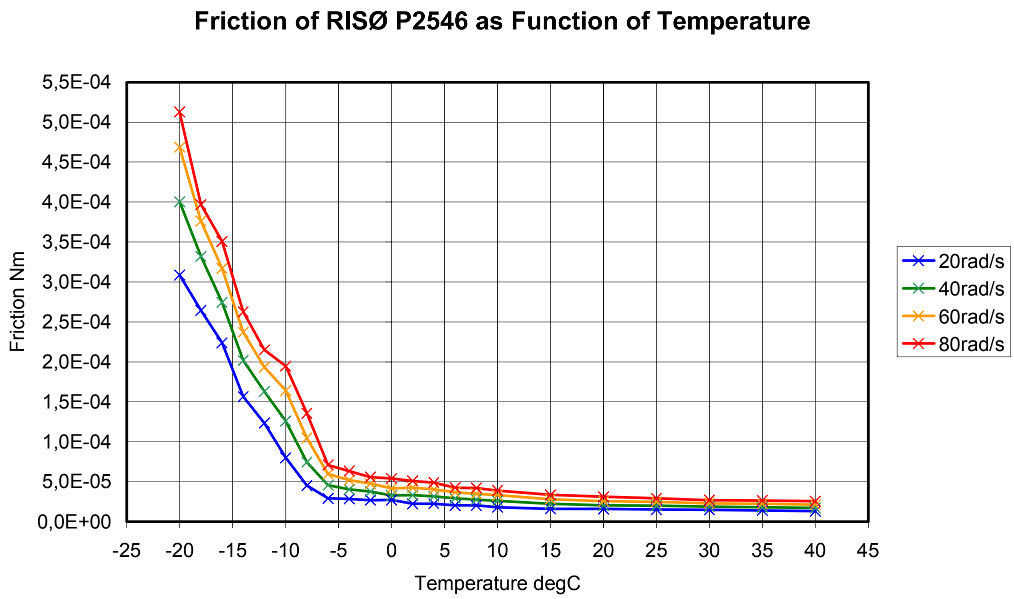

Figure 3-19 Friction as function of temperature

4 Time Domain Modelling

4.1 The Time Domain Cup Anemometer Model

The basis for this model is described in Ref. 1. The model takes account of mass forces, friction and aerodynamic forces. Aerodynamic forces are normalized to a torque coefficient function, which for given values of wind speed and angular speed is corrected with an angular response function.

Wind speed definitions

Consider a time dependent 3D wind speed vector with a longitudinal component u, a transversal component v, and a vertical component w as input to the cup-anemometer.

$$\vec{U} = (u, v, w)$$

The "horizontal" wind speed measures only the horizontal wind speed components (length of the wind speed vector, excluding the vertical component):

$$\left|\vec{U}\right| = \int_t \sqrt{u^2 + v^2}$$

If the cup anemometer has a cosine angular response, the vertical component w automatically is filtered away, and it covers completely the "horizontal" wind speed definition.

The "vector" wind speed measures all three vector components (length of the wind speed vector):

$$\left|\vec{U}\right| = \int_t \sqrt{u^2 + v^2 + w^2}$$

If the cup anemometer has a flat angular response, then it covers completely the "vector" wind speed definition.

The difference between these two definitions is dependent on the turbulence intensity. For 15% turbulence in a flat terrain, the difference is about 0.5%, and for 30% turbulence it is about 1%.

Angular response

The angle of the wind incident upon the cup rotor is:

$$\alpha = A\tan\frac{w}{\sqrt{u^2 + v^2}}$$

The angular response of the cup-anemometer is thus:

$$U = F_\alpha(\alpha, \left|\vec{U}\right|) \cdot \left|\vec{U}\right|$$

where $|\vec{U}|$ is the length of the instantaneous three dimensional wind speed vector, $F_\alpha(\alpha, |\vec{U}|)$ is the angular response function (interpolation in table) and U is the driving wind speed to the cup-anemometer rotor, i.e. the equivalent wind speed perpendicular to the rotor shaft.

Governing equations

The torque on the rotor is a sum of aerodynamic forces and friction forces:

$$Q = Q_A(\lambda_{QA}) + Q_f(T, \omega)$$

The aerodynamic torque is found from the aerodynamic torque coefficient curve through the aerodynamic speed ratio:

$$Q_A = \frac{1}{2}\rho_\tau AR(U - U_t)^2 C_{QA}(\lambda_{QA})$$

$$\lambda_{QA} = \frac{\omega R}{U - U_t}$$

Bearing friction is interpolated between frictions at different temperatures:

$$Q_f = f_0(T) + f_1(T)\cdot\omega + f_2(T)\cdot\omega^2$$

The driving torque differential equation is:

$$I\frac{d\omega}{dt} = Q$$

from which the rotational speed is calculated numerically with the Euler method with small time steps in time domain:

$$\Delta\omega = \frac{1}{I}Q\Delta t$$

4.2 Fitting of Data to Cup Anemometer Model

The torque measurements on the cup anemometer, measured at a certain temperature, shall be fitted to both the accredited calibration line, measured at another temperature, and the cup anemometer model. The fitting to the accredited calibration line is necessary for the model to accomplish all static and dynamic characteristics. The fitting includes an offset correction of the torque measurement ΔQ_m and determination of a threshold wind speed U_t.

The speed ratio is defined as:

$$\lambda = \frac{\omega R}{U - U_t}$$

where the threshold wind speed U_t is smaller than the calibration offset B_{cal}.

The accredited calibration at temperature T_{cal}=20,2°C and air density $\rho_{cal} = 1,221 kg/m^3$ is:

$$U = A_{cal} f + B_{cal} = A_{cal}\frac{N}{2\pi}\omega + B_{cal} = 0,62251 ms^{-1}/Hz\cdot f + 0,241 m/s$$

The aerodynamic torque coefficient is derived from the measured torque at ambient temperature T_τ=10,3°C and air density ρ_τ=1,263 and added bearing friction at this temperature:

$$C_{QA} = \frac{Q_m(U,\omega) + Q_f(T_\tau,\omega)}{\frac{1}{2}\rho_\tau AR(U-U_t)^2}$$

The measured torque was corrected with the value $\Delta Q_m = 0,000205602Nm$, and the threshold wind speed was found to $U_t = 0,220m/s$. The measured aerodynamic torque data were fitted to an 11th degree polynomial, with the following expression:

$$C_{qa} = (\lambda - \lambda_{QA0})(a_0 + a_1\lambda + a_2\lambda^2 + ... + a_9\lambda^9 + a_{10}\lambda^{10})$$

The generalized aerodynamic torque coefficient is shown in Figure 4-1 and Table 4-1.

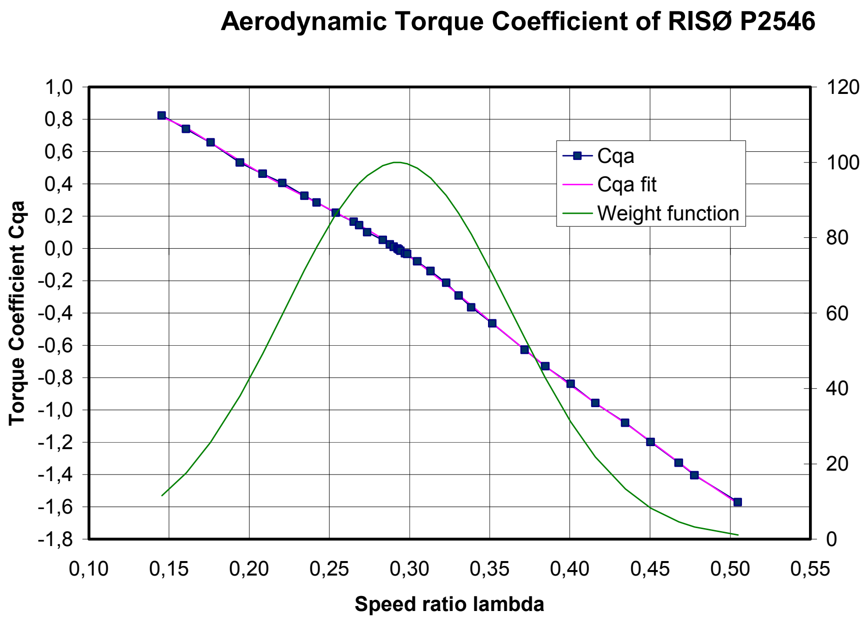

Figure 4-1 Aerodynamic torque coefficient of RISØ P2546 cup anemometer

Table 4-1 Table of aerodynamic torque data fitted to 11th degree polynomial,

a0	5,0961742E+01
a1	-1,1446312E+03
a2	8,6265311E+03
a3	-2,8953636E+04
a4	3,6193685E+04
a5	1,1063195E+04
a6	-3,1746357E+04
a7	-3,1363029E+04
a8	-1,8811059E+02
a9	3,1844481E+04
a10	4,9349945E+04

where $\lambda_{QA0} = 0,2925051$

Geometric cup anemometer data for the time domain model are shown in the Table 4-2

Table 4-2 Geometric cup anemometer data

Parameter		Value
Radius to cup R	[m]	0,058
Cup area A	[m^2]	0,00385

The fitting of data to the cup anemometer model results in a little deviation from the calibration line. Figure 4-2 show deviations of the calibrated points of the accredited calibration from the calibration line, and simulation of the calibration with the time domain model. It is seen, that the data fit the calibration line within 0,0065m/s. The non-linear curve is due to the influence of friction.

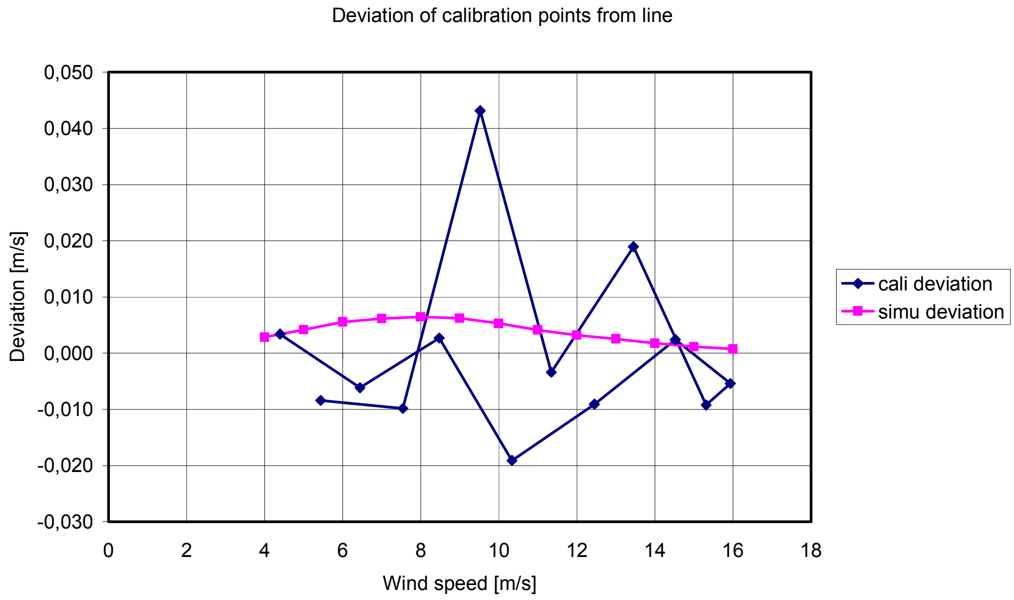

Figure 4-2 Deviations from calibration line for accredited calibration and corresponding simulations

5 Parameter Sensitivity Analysis

The time domain model can be used to calculate responses to different variations of influential parameters. The following chapters show the influences of such variations of parameters with the base in a reference case. This reference case considers measurements of horizontal wind speed and utilizes 25 Hz and ten minute 3D time series of wind speed data at the atmospheric conditions:

- average wind speed 10m/s
- turbulence intensity 10%
- isotropic turbulence
- length scale 500m
- air temperature 10°C
- air density 1,23kg/m^3
- slope of terrain 0°

5.1 Response to Air Temperature Variations

Temperature variations influence the friction. The following figure shows the response at varying temperatures.

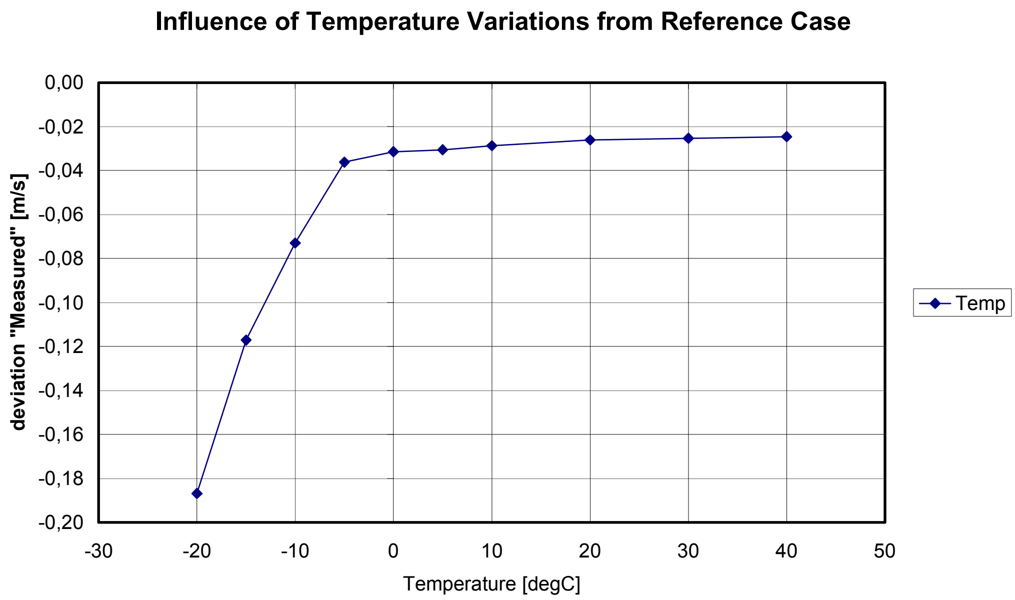

Figure 5-1 Response of RISØ P2546 cup anemometer to temperature variations

5.2 Response to Air Density Variations

Air density variations influence the ratio of friction versus aerodynamic forces. The following figure shows the response at varying air densities.

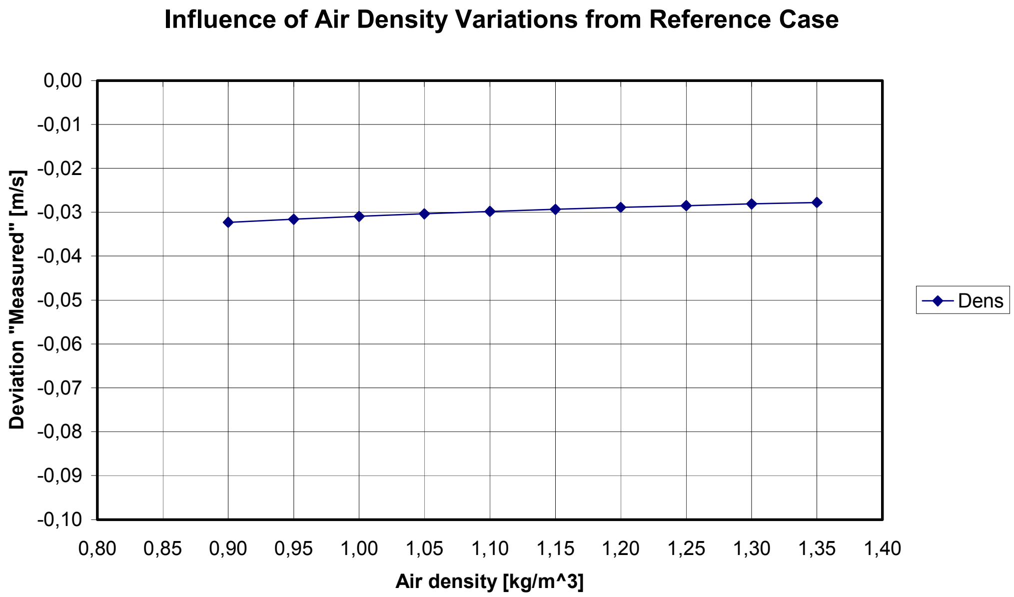

Figure 5-2 Response of RISØ P2546 cup anemometer with air density variations

5.3 Response to Turbulence Variations

Turbulence variations influence the response to angular variations and overspeeding effects. The following figure shows the response at varying turbulence.

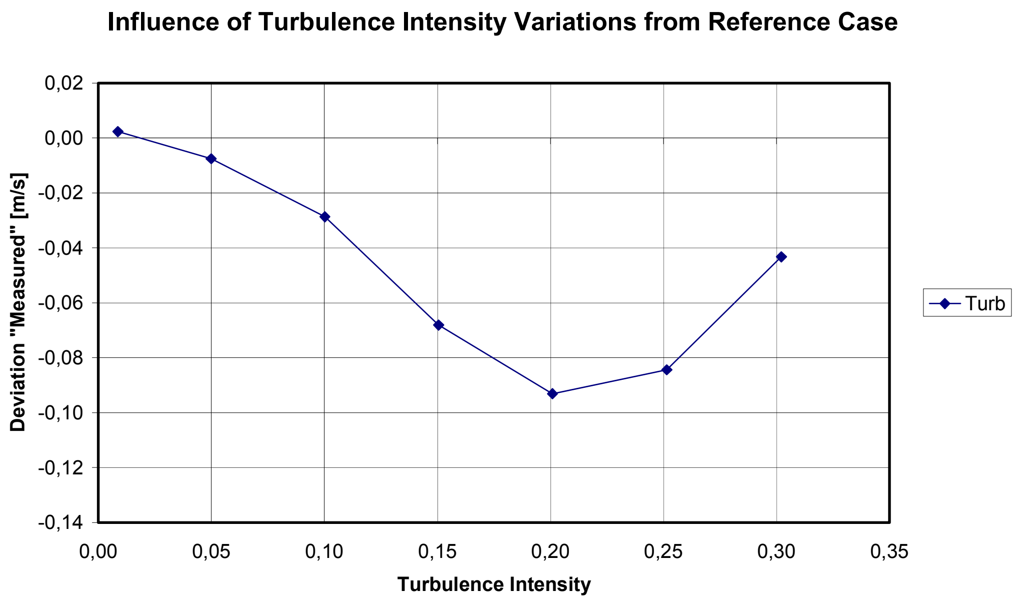

Figure 5-3 Response of RISØ P2546 to turbulence variations

5.4 Response to Length Scale Variations

Length scale variations influence the frequency content of the turbulence and thus the response to overspeeding effects. The following figure shows the response at length scale variations.

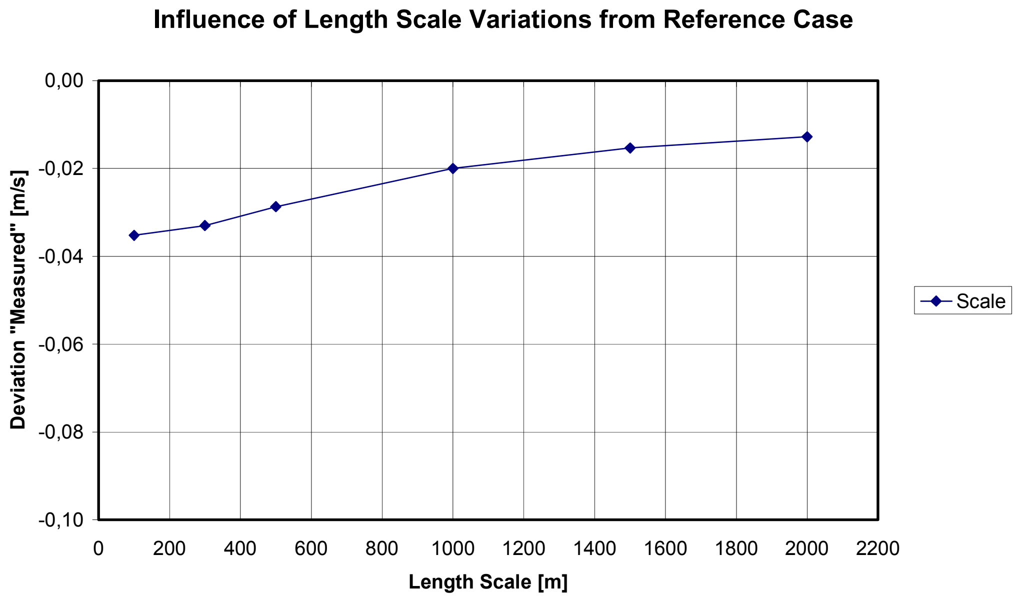

Figure 5-4 Response of RISØ P2546 cup anemometer on length scale

5.5 Response to Inclined Flow

Inclined flow variations influence the angular response. The following figure shows the response at inclination variations.

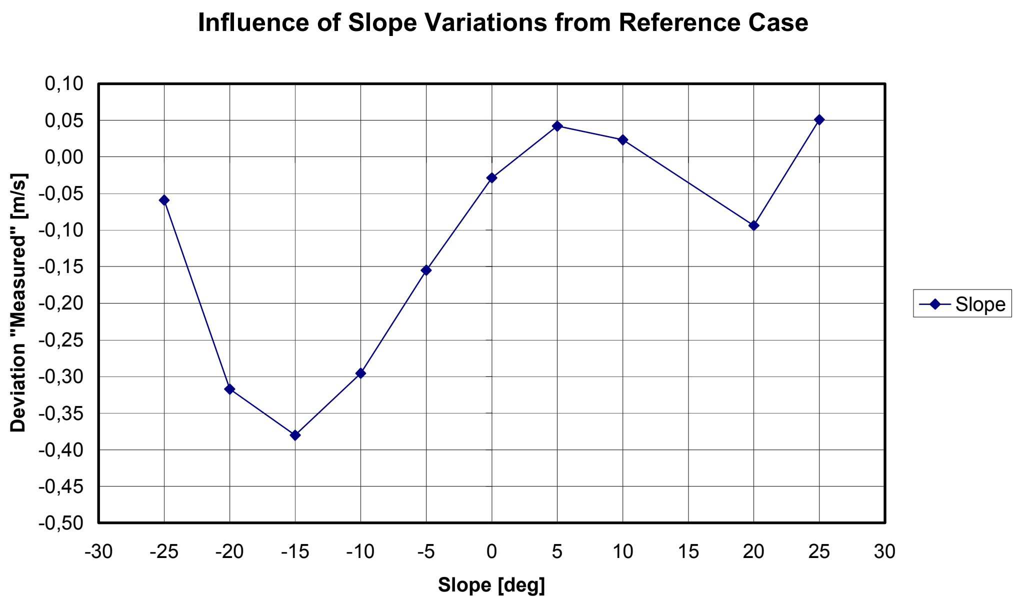

Figure 5-5 Response of RISØ P2546 on variations in slope of terrain

5.6 Response to Plane Sinusoidal Longitudinal Wind Speed Fluctuations

The response to sinusoidal longitudinal wind speed was simulated at 25Hz. Ten minute data files with 3D artificial wind were made, from which the response was calculated. The following figure shows a time trace at 8m/s and 23% turbulence at the beginning of one ten minute data series. The calculations always start in equilibrium at the starting wind speed. It is seen, that within one cycle, the cup anemometer has already reached a steady response.

All gust measurements that were made in the FOI wind tunnel have been simulated and are presented in the figures below.

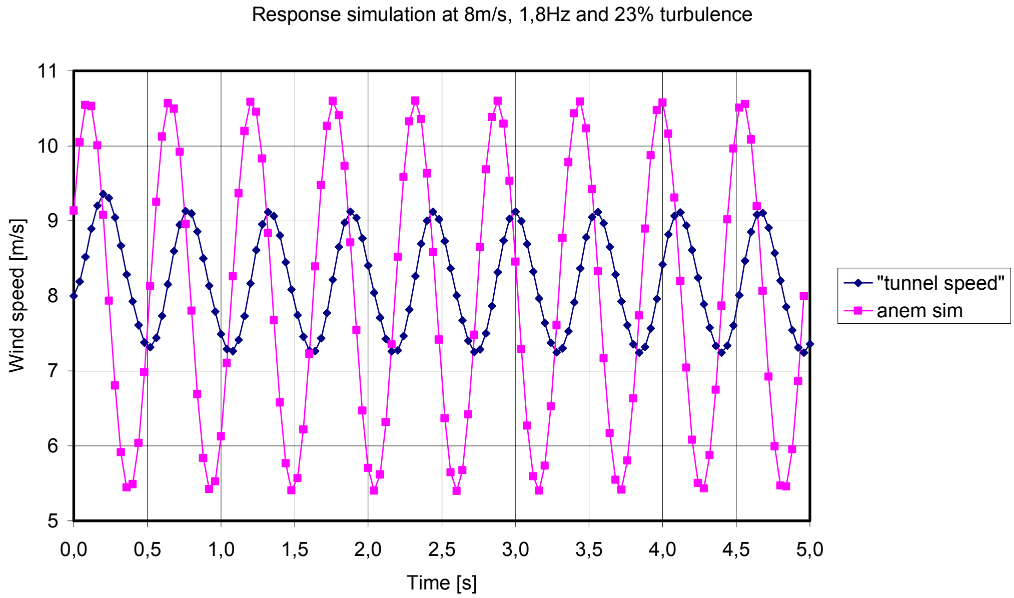

Figure 5-6 Time domain response of sinusoidal wind speed

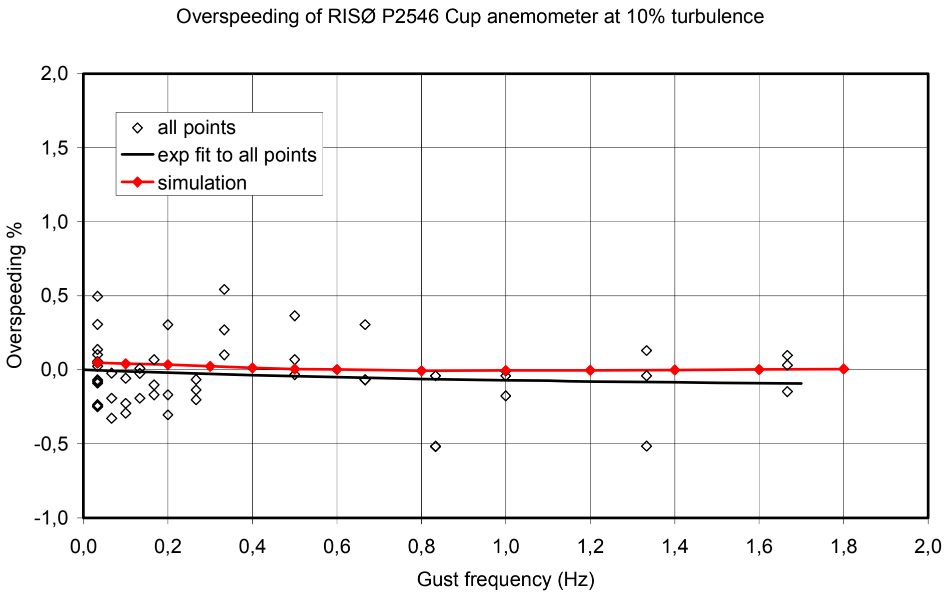

Figure 5-7 Overspeeding at 8m/s and 10% turbulence

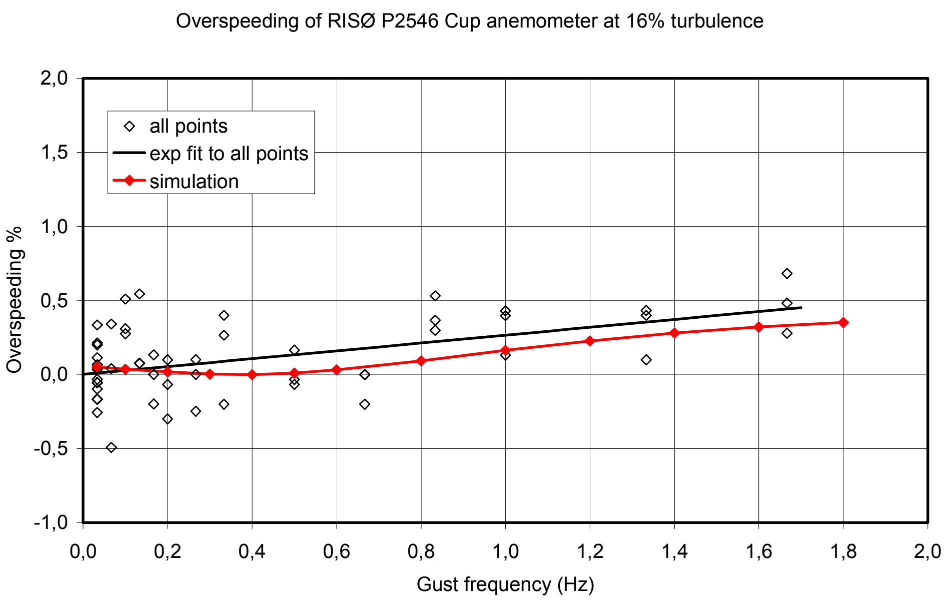

Figure 5-8 Overspeeding at 8m/s and 16% turbulence

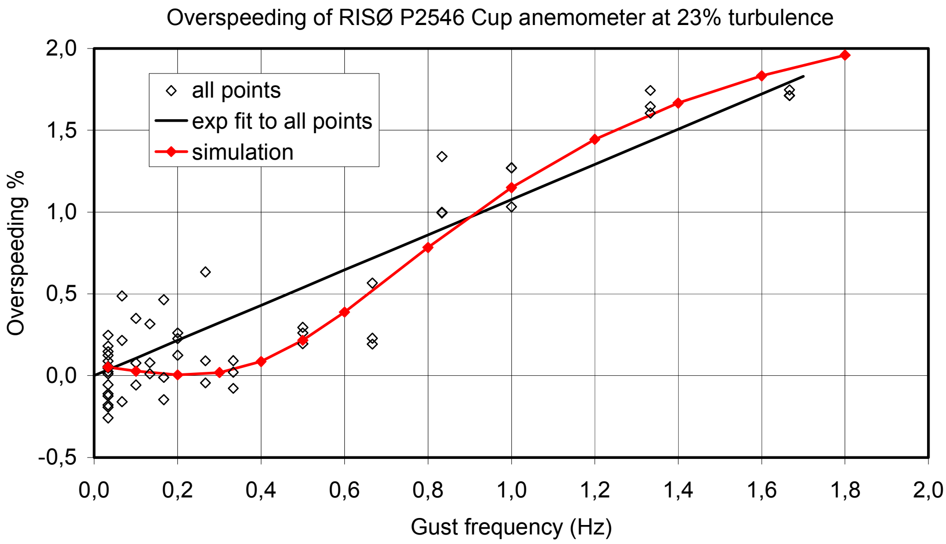

Figure 5-9 Overspeeding at 8m/s and 23% turbulence

The simulations are seen to predict quite good the measured overspeeding. Especially at 23% turbulence, the simulated data follow the measured data very nicely, and the sharp increase from 0,4Hz and upwards is simulated very accurately. At 10% turbulence, there seem to be a loop in the measured data points, which is not shown in the simulation. Up to 0,3Hz the overspeeding seem to take a negative loop and from 0,3Hz to 0,7Hz it takes a positive loop. This shows, that the cup anemometer has a small sensitivity to low frequencies. The reason why the simulation does not include these small variations is, that the torque coefficient curve needs to be even more detailed than the 11th power polynomial fit. For the accuracy of the analysis in this report, though, this is anticipated not to have any significant influence.

6 CLASSCUP Classification

The cup anemometer is now analysed in order to make a classification of operational uncertainties according to the CLASSCUP classification procedure, Ref. 1 and 7.

6.1 Classification Ranges

The classification is divided into four categories, two climatologic ranges and two wind speed definitions, the vector wind speed (including all turbulence components) and the horizontal wind speed (excluding the vertical turbulence component). The climatologic ranges are shown in the following two tables.

Table 6-1 *Normal Range (Typical operational ranges for wind turbine power performance measurements at ideal sites, Ref. 8)*

Parameter	Normal range		
	Min	Ave	Max
Wsp (10min) [m/s]	4	4-16	16
Turb.int.	0,03	0,10	0,12+0,48/V
Turbulence structure $\sigma_u/\sigma_v/\sigma_w$.	1/0,8/0,5 (non-isotropic turbulence)		
Length scale L_k [m]	100	500	2000
Air temp. [°C]	0	10	40
Air density [kg/m^3]	0,9	1,23	1,35
Slope [°]	-5	0	5
Ice, snow, rime conditions	Not included		

Table 6-2 *Extended Range (Typical operational ranges for wind turbine power performance verification measurements including complex terrain)*

Parameter	Extended range		
	Min	Ave	Max
Wsp (10min) [m/s]	4	4-16	16
Turb.int.	0,03	0,10	0,12+1,13/V
Turbulence structure $\sigma_u/\sigma_v/\sigma_w$.	1/1/1 (isotropic turbulence)		
Length scale L_k [m]	100	500	2000
Air temp. [°C]	-10	10	40
Air density [kg/m^3]	0,9	1,23	1,35
Slope [°]	-15	0	15
Ice, snow, rime conditions	Excluded		

The classification ranges are a combination of an absolute and a relative deviation, defined as:

$$ClassRange = ClassIndex \cdot (0.1m/s + 0.01 \cdot U)/2$$

The ClassIndex is set to fixed numbers: 0.5, 1, 2, 3, 5. The evaluation of a cup anemometer should find the ClassRange for normal and extended climatologic ranges in order to derive the ClassIndex, to be compared to the fixed ClassIndex numbers. The actual ClassIndex or the fixed ClassIndex should be used in the cup anemometer uncertainty evaluation regarding operational characteristics. Calibration uncertainty, uncertainty due to mast and boom effects, and eventually terrain uncertainty in power performance measurements, Ref. 8, shall be added separately.

6.2 Wind Generation Model

The time domain model of the cup anemometer is able to calculate the response to any time domain input of wind speed. From the ranges of operation, artificial wind is generated as input time series.

The turbulence model used to generate the 3D wind files for the calculations in this report is made by Jacob Mann. Ten minute time series of 25Hz data are made for each calculation. The input data for the model are taken from the operational ranges of the parameters in the tables above. In this way all relevant operational conditions can be tested and a sufficient database to determine overall deviations is made.

6.3 Classification Response Plots

The ClassIndex plot of RISØ P2546 for normal category is based on 336 calculations of 10min time series of 25Hz data, derived from the range of climatologic values in Tables 6-1 and 6-2. The ClassIndex plot for extended category is based on 560 calculations. The classification is made for the horizontal wind speed definition only.

The result for the extended category, 6,24, is higher than was found for earlier cup anemometer type P2445, Ref. 7, which concluded that the extended category was 5. The reason for the higher ClassIndex of P2546 is that the simulations covered more values in the operational range intervals, and not just the extremes.

6.4 Summary of CLASSCUP Classification

The following table summarizes the classification according to Ref. 7.

Table 6-3 CLASSCUP ClassIndex of RISØ P2546 cup anemometer with respect to horizontal wind speed definition, fixed ClassIndex values in parenthesis

Definition	Normal	Extended
Horizontal	1,99 (2)	6,24 (above 5)

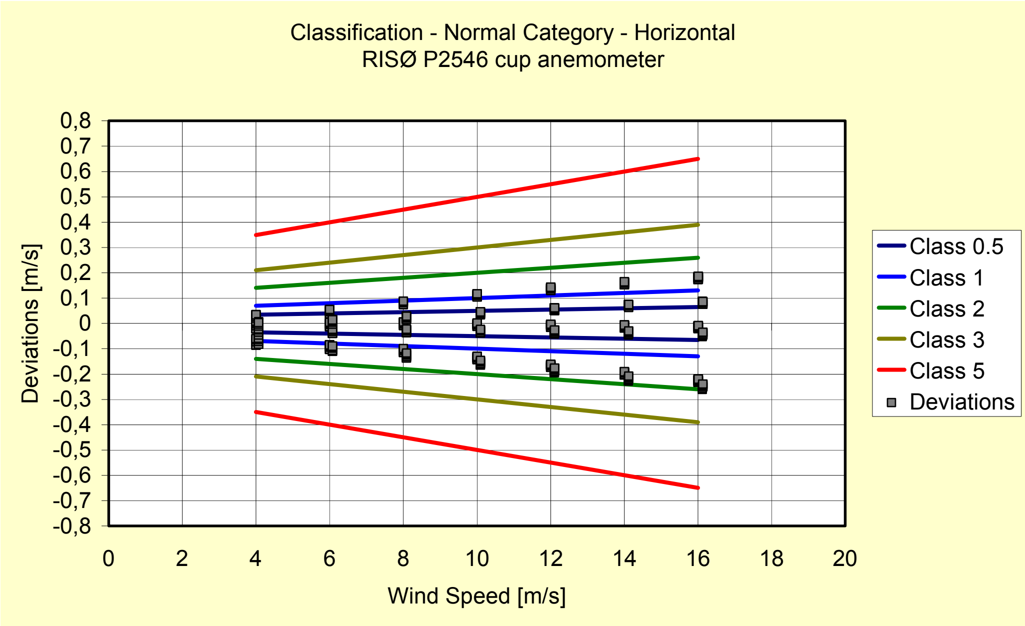

Figure 6-1 Classification of RISØ P2546 cup anemometer Normal category - Horizontal wind speed definition

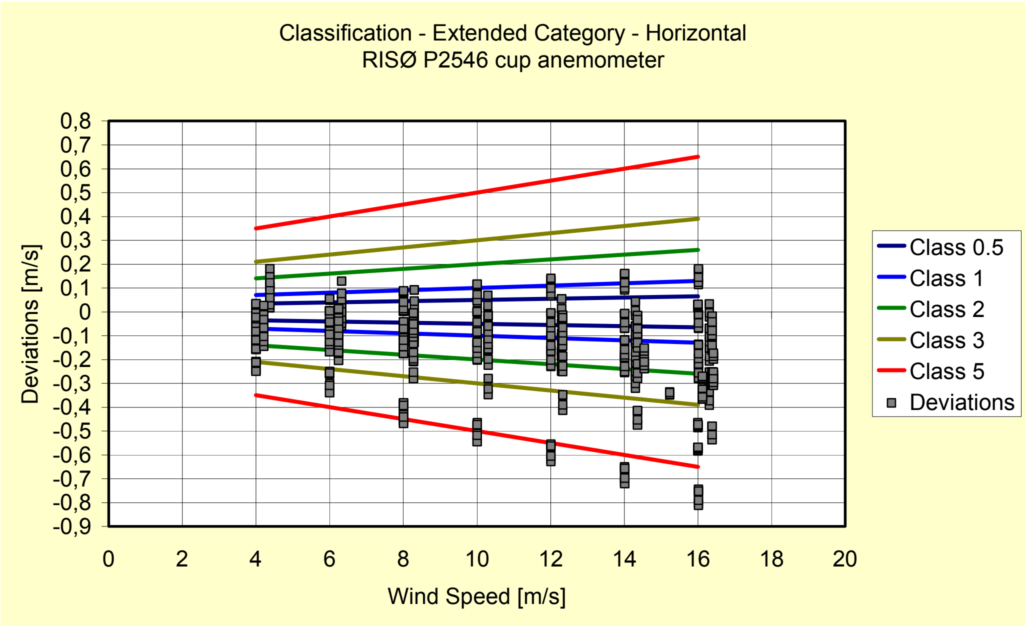

Figure 6-2 Classification of RISØ P2546 cup anemometer Extended category - Horizontal wind speed definition

7 Compliance with Danish Certification System Requirements

The Danish certification system has set up requirements for cup anemometers used for power performance measurements in relation to wind turbine certification. A sub-committee set up the requirements with participants from testing institutes connected to the Danish certification system. The requirements are collected in document Ref. 2.

The characteristics of the RISØ P2546 cup anemometer are related to these requirements in the following.

1) The wind speed is referred to the horizontal wind speed, which is required

2) The angular characteristics of the RISØ P2546 cup anemometer are shown in the following figure, in which the requirements are also shown.

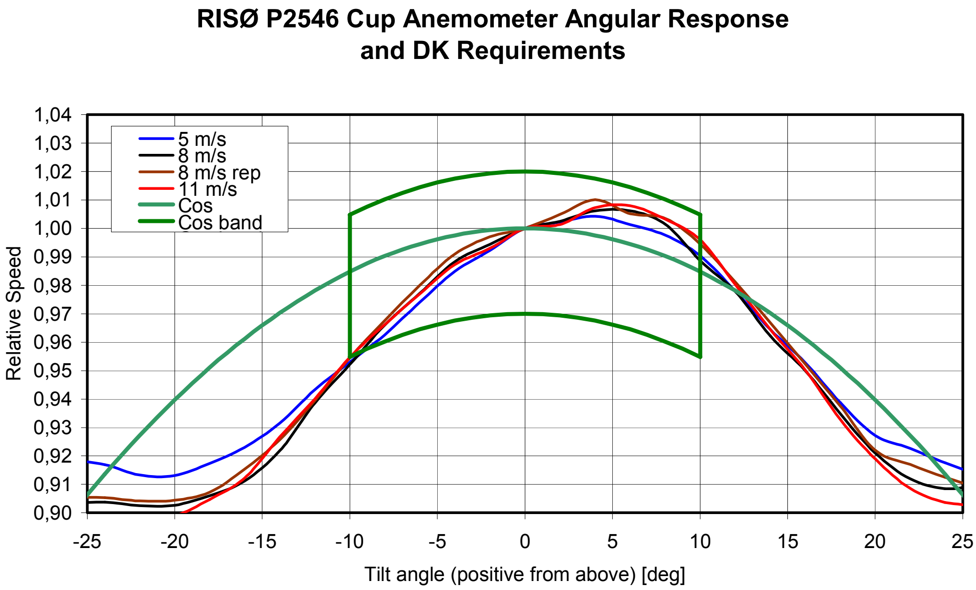

Figure 7-1 Angular characteristics of RISØ P2546 cup anemometer and DK certification requirements

The angular characteristics are seen to meet the requirements. At -10°, though, the characteristics are on the limit as the curves coincide with the requirement cos band.

3) The distance constant was found in chapter 8 using the IEA recommendation. The average of the measured distance constant was 2,20m, which is below the required 3m.

4) The overspeeding was measured according to the method developed in the CLASSCUP project and the results are shown in chapter 6 for 16% turbulence up to 1,8Hz. The average overspeeding is maximum 0,5% at 1,8Hz. The average overspeeding is above a minimum of -0,2%. The simulated overspeeding at higher frequencies is shown in the following figure. The maximum level at

higher frequencies is seen not to exceed 0,5% either. The overspeeding is thus below 3% and above -0,5% at 15% turbulence, which is required.

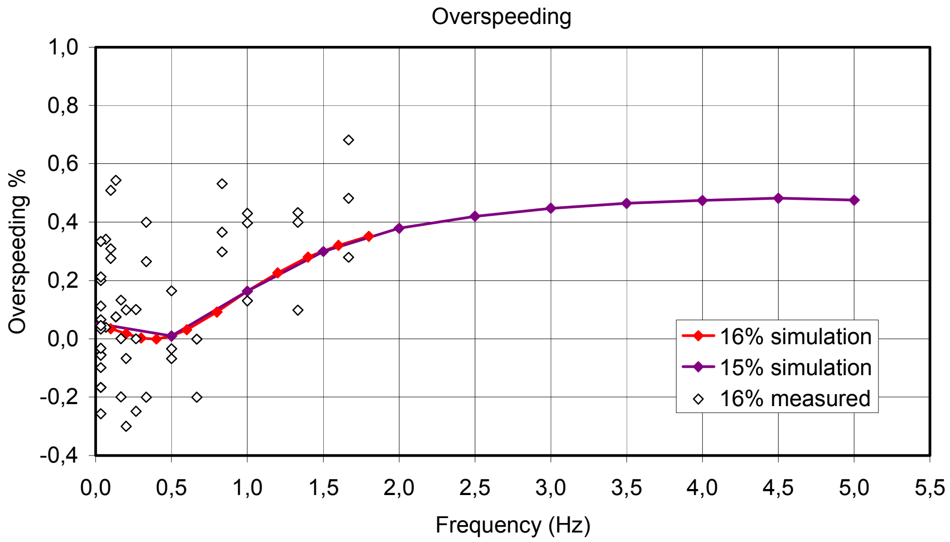

Figure 7-2 Calculated overspeeding at 15% turbulence

5) The friction requirements are shown in the upper red curve in the figure below. All friction data of the P2546 cup anemometer are seen to be substantially lower than the requirement at all temperatures from -6°C to 40°C.

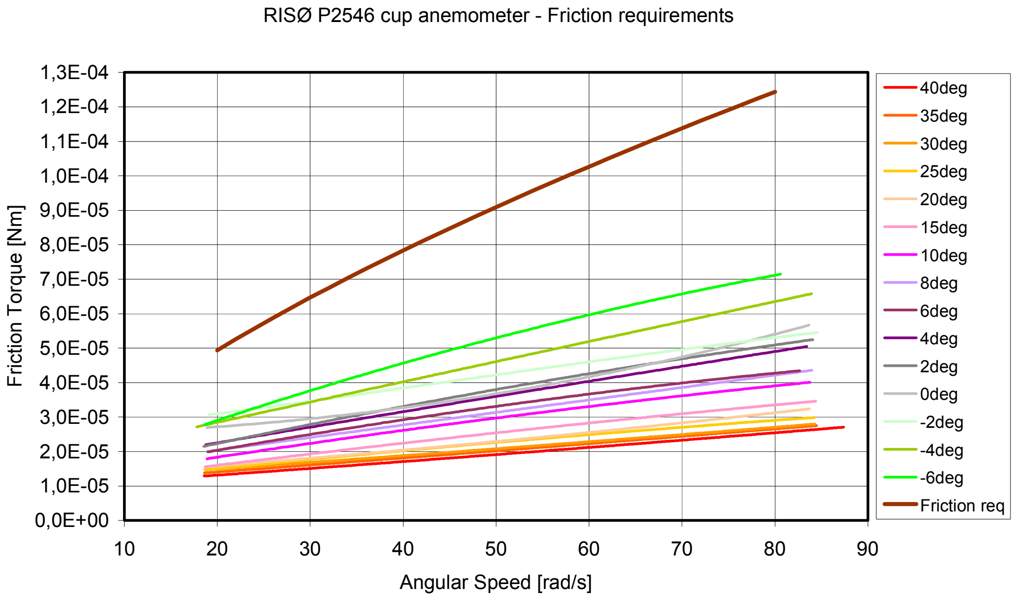

Figure 7-3 Friction requirements in DK certification system and friction of RISØ P2546

6) The cup anemometer is not known in calibration or field measurements to have any positions of the rotor at which the torque is zero or negative. It does always start at low wind speeds, independent of rotor position, and thus meets the requirements.

7) The cup anemometer body is rotational symmetric and the cable is mounted from below and positioned in the mounting tube. Therefore, the calibration is independent of wind direction, and therefore, the requirements are met.

8) The linearity always meets the requirement $r \geq 0.99995$. Calibrations are made by accredited calibration institutes, which always meet the requirement. Otherwise, instruments shall not be used.

9) The cup anemometer is ultimo 2002 CE marked.

10) The requirements of a field comparison is not met, since this should be made with the same type of cup anemometer. Field comparisons with a directionally calibrated sonic anemometer are planned, also for comparison of wind tunnel and laboratory tests with field operation.

I) The anemometer has three cups as required

II) The neck is long and slim and rotational symmetric as required

III) The body is slender and symmetric as required

IV) The line connection is through the bottom of the cup anemometer and the supporting tube as required

8 Compliance with IEC61400-121 Committee Draft

The CD of IEC 61400-121 proposes a procedure for classification of cup anemometers, Ref. 3.

The characteristics of the RISØ P2546 cup anemometer are related to these requirements in the following.

<u>Angular characteristics</u>

The angular characteristics is applied a weighting due to turbulence. The turbulence shall be 20% and the relation between the vertical and longitudinal turbulence components shall be 0.8. This corresponds to 16% isotropic turbulence, which is shown in the following figure. The response may not deviate by more than 1% for a class 1 anemometer.

It is seen that the cup anemometer only meets the requirements from -20° to -17°.

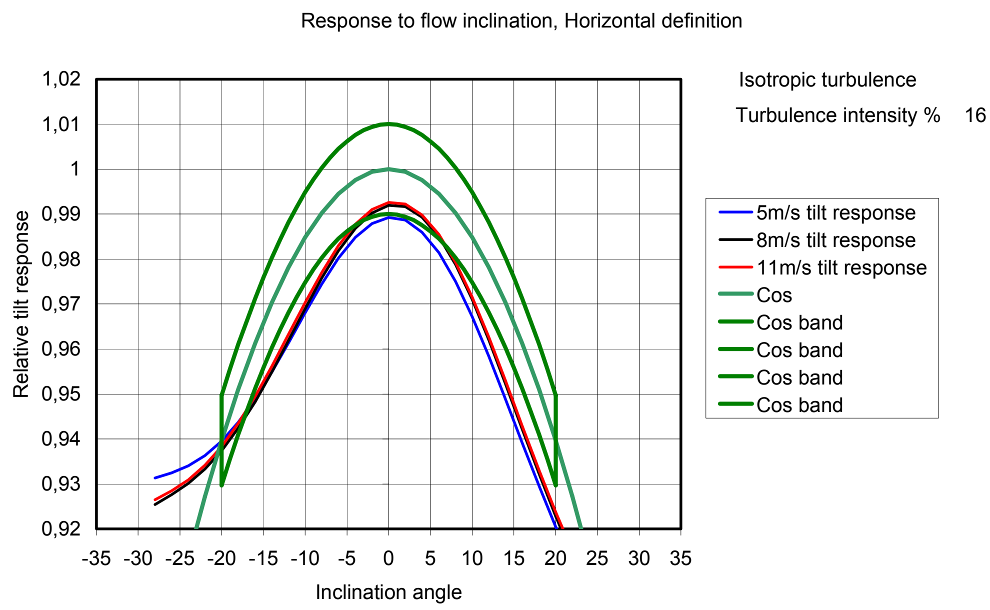

Figure 8-1 Tilt response relative to cup anemometer requirements of IEC 61400-121 CD

<u>Friction in bearings</u>

The friction may not deviate more than 1% for a class 1 anemometer. In the following figure, the simulated deviation from the calibration is possible for temperature down to -5°C.

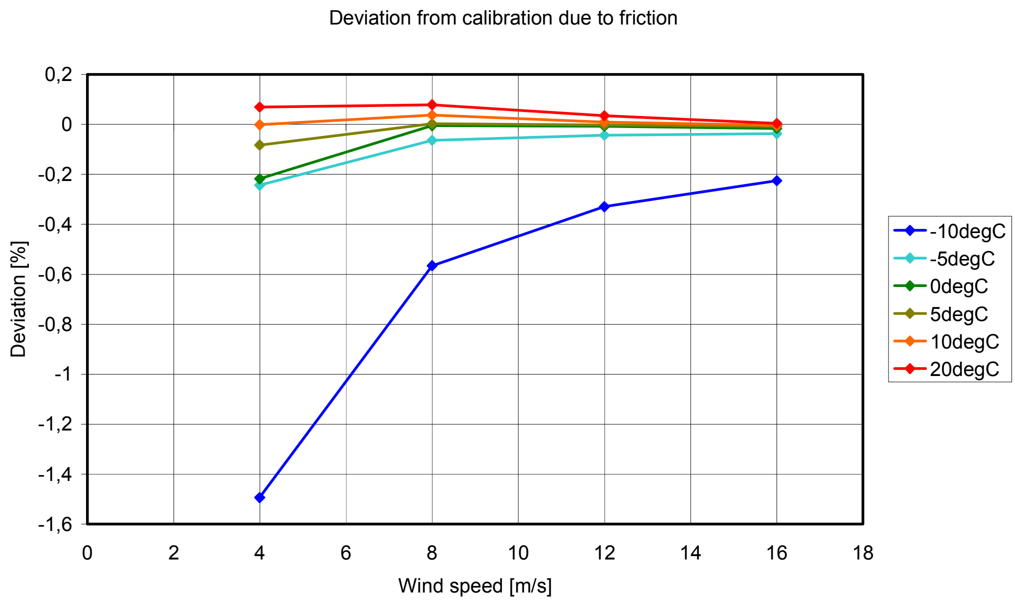

Figure 8-2 Deviation from calibration due to temperature and friction

<u>Field comparison in flat terrain</u>

A field comparison with a directional sonic anemometer in flat terrain is planned, but available at present. A comparison with the P2445 type cup anemometer was made in the SITEPARIDEN project (Antoniou 2001). The results from this report are not unambiguous, but the results seem to be at the limit of -1%, which corresponds well with the calculated tilt response and calculated overspeeding.

9 Conclusions

The characteristics of the RISØ P2546 cup anemometer were investigated in detail by wind tunnel and laboratory tests. The characteristics include accredited calibration, tilt response measurements for tilt angles between -40° to 40°, gust response measurements at 8m/s and turbulence intensities of 10%, 16% and 23%, step response measurements at step wind speeds 3,7, 8, 11,9 and 15,2m/s, measurement of torque characteristics at 8m/s, rotor inertia measurements and measurements of friction of bearings at temperatures -20°C to 40°C.

The cup anemometer characteristics were fitted to a time domain cup anemometer model. The model was verified to simulate the wind tunnel measurements with rather high accuracy. The characteristics were transformed into the CLASSCUP classification scheme, and the result for horizontal wind speed definition was a normal category class 2 (1,99) and an extended category more than class 5 (6,24).

The cup anemometer characteristics were related and verified to comply with the cup anemometer requirements in the Danish certification system. At -10° in tilt response, though, it is on the limit. The characteristics were also related to the cup anemometer requirements in the IEC 61400-121 Committee Draft. The result was that they did not comply regarding tilt response, except for a small range about -20°. Friction was in compliance down to -5°C. Field comparison with a sonic has not been made for the specific type P2546 for the time being.

10 References and Additional Literature

10.1 References

1 Development of a Standardised Cup Anemometer suited to Wind Energy Applications, J-Å Dahlberg, T.F.Pedersen, D.Westermann

2 Technical Criteria for the Danish Approval Scheme for Wind turbines. Requirements to Cup Anemometers Applied for Power Curve Measurements under the Danish Approval Scheme for Wind Turbines, 14/1-2002 The Danish Energy Agency

3 88/163/CD Committe Draft (CD) IEC 61400-121 Ed.1 Wind Turbines - Part 121: Power performance measurements on grid connected wind turbines.

4 IEA 11. Wind speed measurement and use of cup anemometry, 1. edition 1999

5 MEASNET cup anemometer calibration procedure, Version 1, September 1997

6 ISO 3966 Measurements of fluid flow in closed conduits 1977

7 Development of a Classification System for Cup Anemometers - Classcup, Troels Friis Pedersen, RISØ-R-1348(EN), December 2002

8 IEC 61400-12, first edition 1998 “Wind turbine generator systems – Part 12: “Wind turbine power performance testing”

10.2 Additional Literature

Additional information of the RISØ cup anemometer can be found in the literature list:

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Pedersen, T.F., Paulsen, U.S.	1997	A procedure for classification of cup-anemometers, EWEC 97, Dublin
Ronsten, G., Dahlberg, J-Å	1996	Calibration of Anemometers in FFA-L2 Wind Tunnel Including Twin Calibration and Tests of Sensitivity to Wind Velocity Gradient and Tilt, FFA TN 1996-51
Siebers, T., Giguére, P.	2001	A Wind Turbine Manufacturer's Perspective on the use of Different Cup-Anemometer Types for Evaluating Wind-Turbine Performance, EWEC 2001, Copenhagen

Annex A Technical Specifications of RISØ P2546 Cup Anemometer

RISØ

Risø National Laboratory
Wind Energy Department
Post Office Box 49
DK-4000 Roskilde
Denmark

P2546A Cup Anemometer

Features

- Low threshold speed
- Low distance constant
- Negligible overspeeding
- Angular response independent of wind speed
- Fully tested temperature performance
- Symmetrical geometry
- No external power source
- Bounce free reed switch

Description

The P2546A Cup Anemometer is a sturdy wind sensor solely constructed by durable materials such as anodized aluminium and stainless steel.
The wind speed is sensed by a three-cup rotor assembly. Permanent magnets mounted on the shaft causes a switch to close and open two times per revolution.
The switch has no bounce and it is equipped with a special built-in mechanism, which reduces the variation in operating time over the frequency range. This feature provides the possibility of obtaining the instantaneous wind speed by measuring the time interval of each revolution.

Specifications

Measuring range	0…70 m/s
Starting threshold	< 0.4 m/s
Distance constant	$\ell_0 = 1.81 \pm 0.04$ m
Standard Calibration	$U = A_0 + B_0 \times f$
Wind speed	U [m/s]
Offset ("starting speed")	$A_0 = 0.27$ m/s
Gain	$B_0 = 0.6201$ m
Output frequency	f [Hz]
Standard deviation of offset	0.014 m/s
Standard deviation of gain	0.027 m
Variation among units	±1%
Nonlinearity	<0.04 m/s
Temperature influence, -15…60°C	< 0.05 m/s

Switching characteristics

Signal type	potential free contact closure
Duty cycle	40…60%
Max switching voltage	30 V
Max. recommended switching current	10 mA
Series resistance	330 Ω, 1 W
Operating temperature range	–35…60°C

The specifications are based on 80 wind tunnel calibrations performed according to the Measnet Cup Anemometer Calibration Procedure.
The specified offset and gain figures represent the mean values of these calibrations.
Variation among units designates the maximum deviation of any unit from the straight line representing these mean values.

All units are run-in for 225 hours at 9 m/s, in order to reduce the initial bearing friction to a level close to the steady state value.

After run-in, bearing friction is tested at –15 °C and at room temperature. The allowed limits for this test assures that the temperature influence on the calibration is within the specified limit.

Annex B Calibration Certificate from DEWI

DEUTSCHER KALIBRIERDIENST **DKD**

Kalibrierlaboratorium für Strömungsgeschwindigkeit von Luft
Calibration laboratory for velocity of air flow

Akkreditiert durch die / *accredited by the*
Akkreditierungsstelle des DKD bei der
PHYSIKALISCH-TECHNISCHEN BUNDESANSTALT (PTB)

DEUTSCHES WINDENERGIE
INSTITUT
WILHELMSHAVEN

Deutscher Akkreditierungs Rat
DAR
DKD-K-28901

Kalibrierschein
Calibration Certificate

Kalibrierzeichen
Calibration label

DKD-K-28901
388_02

Gegenstand *Object*	Cup Anemometer
Hersteller *Manufacturer*	Risoe Dk 4000 Roskilde
Typ *Type*	2546a
Fabrikat/Serien-Nr. *Serial number*	Body: 840 Cup: 1364
Auftraggeber *Customer*	Risoe DK-Roskilde
Auftragsnummer *Order No.*	388_02
Anzahl der Seiten des Kalibrierscheines *Number of pages of the certificate*	3
Datum der Kalibrierung *Date of calibration*	22.04.02

Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
Der DKD ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine.
Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.
This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DKD is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.

Dieser Kalibrierschein darf nur vollständig und unverändert weiterverbreitet werden. Auszüge oder Änderungen bedürfen der Genehmigung sowohl der Akkreditierungsstelle des DKD als auch des ausstellenden Kalibrierlaboratoriums. Kalibrierscheine ohne Unterschrift und Stempel haben keine Gültigkeit.
This calibration certificate may not be reproduced other than in full exept with the permission of both the Accreditation Body of the DKD and the issuing laboratory. Calibration certificates without signature and seal are not valid.

Stempel *Seal*	Datum *Date*	Leiter des Kalibrierlaboratoriums *Head of the calibration laboratory*	Bearbeiter *Person in charge*
Deutscher Kalibrierdienst DKD-K-28901	22.04.02	Dipl. Phys. D. Westermann	P. Busche Dipl. Ing. P. Busche

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DKD-K-28901
388_02

Kalibriergegenstand *Object*	Cup Anemometer	
Kalibrierverfahren *Calibration procedure*	MEASNET - Cup Anemometer Calibration Procedure - 9/1997 ISO 3966 – Measurement of fluid in closed conduits - 1977	
Ort der Kalibration *Place of calibration*	Windtunnel of University of Oldenburg	
Meßbedingungen *Test Conditions*	wind tunnel area 1)	8000 cm^2
	anemometer frontal area 2)	228 cm^2
	diameter of mounting pipe 3)	27 mm
	blockage ratio 4)	0.029 [-]
	blockage correction 5)	0.999 [-]
	tunnel calibration 6)	0.998 [-]
	average DEWI reference 7)	Thies 100: 10.07 m/s
	present DEWI reference 8)	10.07 m/s
Umgebungsbedingungen *Air conditions*	air temperature	20.2 deg
	air pressure	1031.4 hPa
	relative air humidity	39.7 %
Dateiinformation *File* info		c:\ak\aktuell\388_02.txt
Anmerkungen *Remarks*	-	
Auswertesoftware *Software version*	20	

1) Querschnittsfläche der Auslaßdüse des Windkanals

2) Vereinfachte Querschnittsfläche (Schattenwurf) des Anemometers incl. Montagerohr

3) Durchmesser des Montagerohrs

4) Verhältniss von 2) zu 1)

5) Korrekturfaktor in der Geschwindigkeit bedingt durch die Verdrängung der Strömung durch das Anemometer

6) Geschwindigkeitsverhältnis am Ort des Anemometers zur Meßebene

7) Mittelwert der Geschwindigkeiten des Refernzanemometers

8) Aktueller Wert der Geschwindigkeit des Referenzanemometers

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Meßergebnis:
Result:

Stroemungs-geschwindigkeit	Anzeige Anemometer	Erweiterte Messunsicherheit
m/s	1/s	m/s
4.395	6.667	0.13
6.441	9.969	0.08
8.473	13.219	0.12
10.338	16.250	0.12
12.449	19.625	0.14
14.521	22.935	0.14
15.935	25.219	0.14
15.313	24.226	0.14
13.450	21.188	0.13
11.346	17.844	0.12
9.525	14.844	0.11
7.541	11.742	0.12
5.434	8.355	0.13

Angegeben ist die erweiterte Meßunsichherheit, die sich aus der Standardmeßunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DKD-3 ermittelt. Der Wert liegt mit einer Wahrscheinlichkeit von 95% im zugeordneten Wertintervall.

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MEASNET Appendix

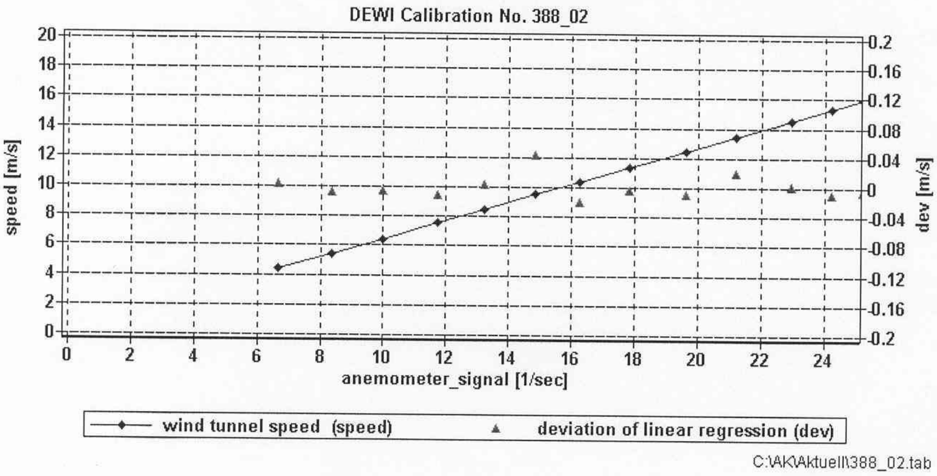
1. Results

DKD calibration no.	388_02
type	2546a
serial number	840
cup number	1364
date	22.04.02
file	c:\ak\aktuell\388_02.onl
DEWI version	20
air temperature	20.2 deg
air pressure	1031.4 hPa
air humidity	39.7 %

linear regression analysis

slope	0.62251 m
offset	0.241 m/s
correlation coefficient	0.999991

remarks -



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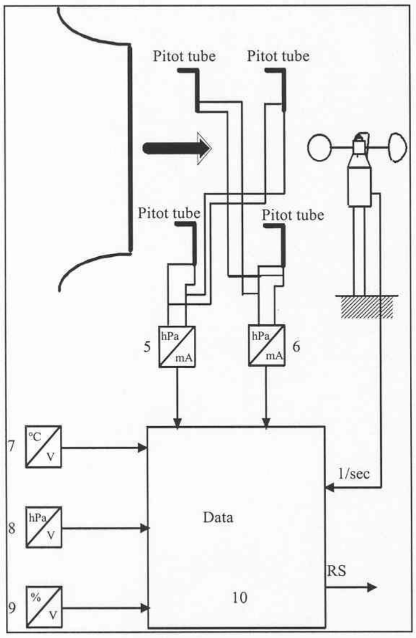
2 Instrumentation



Description of the data acquisition system

1 - 4 Pitot tube
Type: Airflow (ISO 3966)
Year: 1994
Calibration: No; ISO 3966 [1]

5 Pressure transducer
Type: ASHCROFT XLdp
Year: 1993
Calibration: 5/99

6 Pressure transducer
Type: ASHCROFT XLdp
Year: 1993
Calibration: recalibration DEWI

7 Thermometer
Type: Rotronic MP 300/340
Year: 1994
Calibration: checked with temperature standard

8 Barometer
Type: Vaisala PTA 427
Year: 1994
Calibration: checked with pressure standard

9 Humidity
Type: Rotronic MP 300/340
Year: 1994
Calibration: No

10 Data logger
Type: Ammonit V 492 B
Year: 1994
Calibration: checked with calibrated multi meter

Reference Pressure transducer
Type: SETRA D 239
Year: 2001
Calibration: DKD 11/01

Wind Tunnel: University of Oldenburg

Remark: Pressure standard is traceable calibrated by the German 'Eichamt' in 10/97
Temperature standard is traceable calibrated by the German 'Eichamt' in 4/94
The multi meter is traceable calibrated by the German 'DKD' in 5/99

3 Deviation to MEASNET Procedure

1. The time to get stable flow conditions between two steps in wind speed is approx. 30 seconds (it has been proved for this tunnel that 30 seconds are enough).

2. The humidity sensor is calibrated by the manufacturer.

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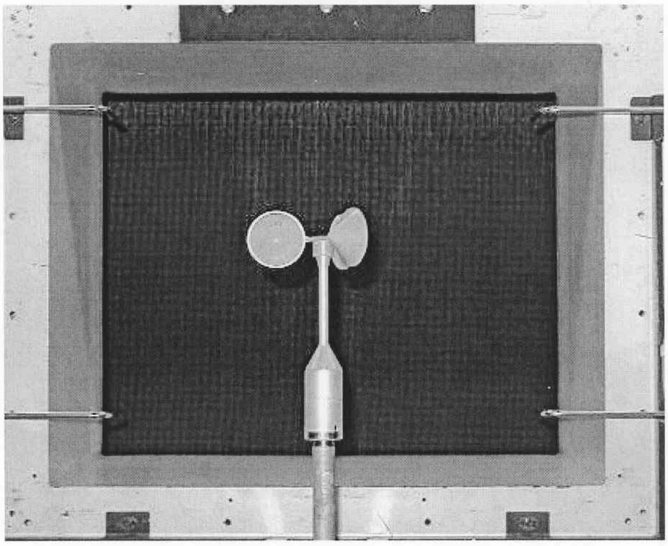

Photo showing the anemometer and the mounting system in the wind tunnel.
The anemometer shown in the photo is not the calibrated one but completely identical with the calibrated anemometer.
Remark: The photo does not show the real proportions, it is distorted by the lens of the camera.

4 References

[1] MEASNET
Cup Anemometer Calibration Procedure
September 1997

[2] ISO 3966 1977
Measurement of fluid flow in closed conduits.

[3] D.Westermann, H. Klug, K. Junior 1999
DEWI Anemometer Calibration Procedure

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Title and authors

Characterisation and Classification of RISØ P2546 Cup Anemometer

Troels Friis Pedersen

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RISØ

Pages	Tables	Illustrations	References
49	10	39	8

Abstract (max. 2000 characters)

The characteristics of the RISØ P2546 cup anemometer were investigated in detail by wind tunnel and laboratory tests. The characteristics include accredited calibration, tilt response measurements for tilt angles between -40° to 40°, gust response measurements at 8m/s and turbulence intensities of 10%, 16% and 23%, step response measurements at step wind speeds 3,7, 8, 11,9 and 15,2m/s, measurement of torque characteristics at 8m/s, rotor inertia measurements and measurements of friction of bearings at temperatures -20°C to 40°C. Characteristics were fitted to a time domain cup anemometer model. The characteristics were transformed into the CLASSCUP classification scheme, and were related to the cup anemometer requirements in the Danish certification system and in the IEC 61400-121 Committee Draft.

Descriptors INIS/EDB

ANEMOMETERS; CALIBRATION; CLASSIFICATION; PERFORMANCE TESTING; SPECIFICATIONS